RECONSTRUCTING PALEOENVIRONMENTAL CHANGE IN LAKE SCUGOG (ONTARIO, CANADA) USING SUBFOSSIL DIATOMS PRESERVED IN LAKE SEDIMENTS

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A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

GRADUATE PROGRAM IN GEOGRAPHY

YORK UNIVERSITY

TORONTO, ONTARIO

October 2021

ABSTRACT

Lake Scugog is a shallow impoundment in Ontario that is facing multiple stressors, especially eutrophication and climate change. This thesis used paleolimnological approaches to reconstruct diatom assemblage responses to climate change and anthropogenic stressors in the east and west basins of Lake Scugog over the last ~150 years, and in the west basin over the Holocene. The east basin experienced a diatom assemblage transition from the heavy, tychoplanktonic *Aulacoisera* to the small, buoyant *Cyclotella* likely indicating increased thermal stratification due to climate change, and an increase in small, benthic *Fragilaria* potentially corresponding to reduced ice cover. In Port Perry Bay, where urban development is most concentrated, small, benthic *Fragilaria* became dominant following the construction of the Lindsay Dam, and no other diatom assemblage changes occurred over the last ~150 years. The Holocene paleoenvironmental history of Port Perry Bay was similar to other records of Holocene climate from southern Ontario.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my supervisor Dr. Jennifer B. Korosi. Without your continuous support and guidance since my undergraduate years – from my honours thesis to summer work, this thesis would not be possible. I really do not think I could possibly finish this thesis on time during a pandemic without your encouragement and support. Words cannot express my gratitude for all the opportunities and all the things I have learned from you. Being your student for all these years is an experience that I will carry with me for the rest of my life.

I would also like to thank Joshua Thienpont, Kristen Coleman and Dr. Kathy L. Young for their valuable support and insights. I have learned so much from you, in and out of the classrooms/labs. Thank you, Josh, especially for helping me collecting the cores – my noodle arms are forever grateful. Thank you, Kristen, especially for being so kind and patient with me whenever I need your help on diatom identification or running the same old R codes. And a big thank you to Kathy for being my supervisory committee member, you made this thesis possible.

To fellow members of the Korosi Lab – Sorin-Alexandru Gruia, Bradley Auger, Amanda Little, Grace Hoskin, Emily Stewart – thank you for always being so supportive, from helping me with lab work to making me laugh. I will always cherish our friendships, and I look forward to seeing each and every one of you getting all the success you deserve in the future.

This thesis being completed was a large part thank to my dearest friends and supporters. Thank you to Januja Jeyarajah, you have always been one of my greatest friends. You know how much our friendship mean to me. Thank you to Mandy Huynh, you have been the anchor for me these past two years. I counted on you to remind me about all the deadlines and homework. Thank you to Laura Walton, I cannot imagine how university would have been for me if I had not had your never-ending support. I learned so much from your kindness and maturity. Thank you to Zachary Myers Theriault, you are my best friend, you keep me sane throughout everything and I love you to the moon and back. Thank you to David Perkins and Tomás Enrique Mercado, even though we are so far apart physically, we have been through so much together and I can always count on you for mental support on just about anything.

Finally, I would like to thank my family. I know we drive each other crazy sometimes, but I would not be here without your love and support. This thesis is dedicated to you.

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CHAPTER ONE: INTRODUCTION

1.1 Background

Climate change has profound implications for the management of freshwater resources, including biodiversity, water quality, flood mitigation and water scarcity risks (Gronewold & Rood, 2019; International Joint Commission, 2003). Climate change can increase surface water temperatures and evaporation, decrease lake ice cover, and alter lake water budget and mixing regimes (Woolway et al., 2020). Even seemingly small responses to climate change can impact lake ecosystems and change water quality and quantity (Woolway et al., 2020). In general, shallow lakes are very sensitive to the ecological and hydrological impacts of climate change (Meerhoff et al., 2007)

This thesis focused on Lake Scugog – a large shallow impoundment (surface area = 68 km^2, mean depth = 1.4 m) in southern Ontario. Lake Scugog was formed in 1844 following the complete construction of the Lindsay Dam (Canadian Genealogy, n.d.), becoming a headwater lake in the greater Kawartha Lakes system. The lake provides critical ecosystem services to Scugog Township and the City of Kawartha Lakes, and is under threat due to multiple stressors compounded by anthropogenic climate change (Kawartha Conservation, 2010). Eutrophication is the biggest stressor for Lake Scugog, and harmful algal blooms have been recorded in recent history (Harrow-Lyle & Kirkwood, 2020a). Climate-warming-induced thermal stratification during ice-free season has also been recorded (Harrow-Lyle & Kirkwood, 2020a). Other lake management challenges include increasing salinity, invasive species and ecosystem degradation, among others (Kawartha Conservation, 2010).

Paleolimnology is a scientific multi-discipline that focus on reconstructing the past climatic and limnological conditions using numerous physical, chemical, and biological proxies preserved in lake sediments (Last & Smol, 2001). Among the proxies, diatoms – a diverse group of microalgae that is well-preserved in lake sediments thanks to their unique silica shells – are excellent indicators of many limnological variables such as pH, nutrients and salinity (Battarbee et al., 2001). By analyzing compositions and shifts of past diatom assemblages, it is possible to reconstruct historical changes in environmental conditions throughout history of Lake Scugog, as well as how the lake ecosystem responded to those changes.

As climate has been variable in the past, a record of paleoclimate variations can provide insights and predictions on current and future lake ecosystem changes. However, Holocene paleoclimate records for southern Ontario and especially the Kawartha Lakes region are still very scarce and in low resolution. Reconstructing Holocene conditions in Lake Scugog will improve our understanding of Holocene climate variability in the Kawartha Lakes watershed that is not very well understood. Furthermore, knowing how the lake responded to both past and current changes can help guide stakeholders in developing adaptation and mitigation strategies, with regards to multiple stressors and hydrological variations that might be expected with future climate change.

1.2 Research questions

My thesis reconstructs the post-glacial paleoenvironmental history of the Lake Scugog basin by analyzing diatom subfossil remains preserved in lacustrine sediment cores. My research questions are as follows:

(i) What is the paleoenvironmental history in the west basin of Lake Scugog prior to the establishment of the Lindsay Dam, and how do the inferred changes compare against other paleoenvironmental records from southern Ontario?

(ii) How have diatom assemblages in the two basins of modern-day Lake Scugog responded to multiple stressors over the last ~150 years following the establishment of the Lindsay Dam?

CHAPTER TWO: LITERATURE REVIEW

2.1 Climate Change Impacts to Lakes

A lentic ecosystem refers to still waters, which includes lakes, ponds and wetlands that range from freshwater to brackish to hypersaline waters. The term "lentic" is derived from the Latin *lentus*, meaning sluggish or motionless, in contrast to "lotic" which refers to flowing waters like streams and rivers. Lentic ecosystems are very diverse, and are classified based on numerous factors such as hydrologic regime and vegetations (Marsh & Fairbridge, 1999; Niculae et al., 2021). For example, marshes are wetlands dominated by herbaceous plants as opposed to swamps dominated by woody plants. Bogs and fens are both peat-forming wetlands, but bogs receive most if not all of their water from precipitation while fens also receive nutrients through run-off and groundwater movement. (Federal Geographic Data Committee, 2013). Ponds and lakes are harder to distinguish due to varying definitions and arbitrary naming of water bodies throughout history, but in general, ponds are smaller, shallower and lacking the deep aphotic zone where sunlight cannot reach the bottom (Löffler, 2004; Oertli et al., 2005).

There are approximately 117 million lakes with surface area larger than 2000 m^2, accounting for 3.7% of the Earth's non-glaciated land area (Verpoorter et al., 2014). Lakes provide a broad range of ecosystem services such as hydrological regulation, recreation and fisheries (Schallenberg et al., 2013), as well as support a great proportion of the global biodiversity with many new species discovered every year, including many endemic species confined to small ranges of ecosystems (Abell et al., 2008). However, lakes around the world are already being affected by the combined effects of direct human impacts and anthropogenic climate change (Niculae et al, 2021, Woolway et al., 2020). Even small shifts in surface energy balance, water balance and wind mixing with climate change could result in lake physical and

ecological changes (Woolway et al., 2020) that are expected to accelerate in the future (Havens & Jeppesen, 2018).

Lake ice phenology (the timing of ice breakup and freeze up) is a highly sensitive indicator of changes in climate, thus one of the first impacts that can be observed is decreasing lake ice duration (Hewitt et al., 2018). Lake ice formation is controlled by both climatic factors such as air temperature, precipitation, wind, solar radiation, and non-climatic factors such as lake morphometry, elevation and other hydrologic influences (Brown & Duguay, 2010). Deeper lakes are more susceptible to losing ice cover than shallow lakes, as they take longer to cool and the initial ice during the beginning of ice formation is more prone to be broken up by increased wind speed (Magee & Wu, 2017; Sharma et al., 2019). It is estimated that in the Northern Hemisphere alone, about 14,800 lakes currently experience intermittent winter ice cover, and this number would climb to 35,300 at as little as 2°C increase in air temperature (the goal of the Paris Agreement), and to 90,200 at 4.5°C, impacting the ecosystems and the lives of hundreds of millions of people (Sharma et al., 2019).

As air temperature increases, not only does it take longer for lake ice to freeze, but ice breakup also comes sooner. Historical data from 1855 to 2019 of 20 lakes across the Northern Hemisphere showed that ice formation is 11.6 days later and ice breakup is 8.1 days earlier per century, resulting in ice duration now being 19 days shorter per century on average (Woolway et al., 2020). Under a higher emissions scenario, by 2080–2100, 25% of seasonally ice-covered lakes globally are predicted to be permanently ice-free (Woolway & Merchant, 2019). In the Laurentian Great Lakes region, from 1973 to 2010, the basin saw a wintertime warming trend of +0.4°-0.7°C per decade, which led to a 71% reduction overall in Great Lakes ice cover. Lake Ontario experienced the most severe loss at 88% (Wang et al., 2012). Hewitt et al. (2018)

analyzed data from 1981 to 2015 of nine lakes in the region, showed that lake ice melted 5 days earlier and froze 8 days later. The study predicted that by 2070, lake freeze up could be delayed by 11 days and lake ice breakup could come 13 days earlier on average.

Another consequence of a warming climate is the increase in lake surface water temperature (LSWT). There are many drivers for LSWT such as incoming radiation, lake albedo, mixing and heat storage, which are influenced by other controls such as cloud cover, wind speed, humidity, air temperature (Edinger et al., 1968), and even lake ice cover and LSWT itself, thus creating multiple feedback loops in the surface energy balance (O'Reilly et al., 2015; Woolway et al., 2020). Other factors such as climate-induced shifts in lake tributaries discharge regimes (Råman Vinnå et al., 2018), elevation and depth (O'Reilly et al., 2015) also play a role in regulate LSWT, which further complicate the relationship. An increase in LSWT of only 0.8°C (providing initial water temperature was above 24°C) would increase overall cyanobacterial bloom probability by 20%, and that of toxic blooms by 5% over the next century (Rigosi et al., 2015). An increase by 4% in methane emissions from lakes during the next decade is also expected (O'Reilly et al., 2015), which would further contribute to climate warming and amplifying a positive loop.

From 1985 to 2009, the global lake summer surface water temperatures rose rapidly at the rate of 0.34°C per decade, with lakes in cold regions (mean air temperature < -0.4°C) warming faster than those in warmer regions (O'Reilly et al., 2015). LSWT is projected to warmed up about 2.5°C on average, with the most extreme warming about 5.5°C by 2080-2100 under higher emissions scenario (Woolway & Merchant, 2019). Lake heatwaves – periods of extreme warm LSWT – are predicted to increase from 3.7 ± 0.1 to 5.4 ± 0.8°C in intensity and from 7.7 ± 0.4 to 95.5 ± 35.3 days in duration by the end of the 21st century under a higher

emissions scenario (Woolway et al., 2021). In the Laurentian Great Lakes, LSWT of all five lakes reacts in different ways to warming temperature depending on latitude and depth distribution, with large intra-lake variability as well. Among them, Lake Superior with relatively cold waters is considered the hot spot for LSWT warming as it warmed nearly twice as much as air temperature during July-August-September period from 1995 to 2014 (Toffolon et al., 2020). Central-northern Lake Michigan, and central Lake Huron also warmed up faster than most other parts of the Great Lakes during summertime of the 1982–2012 period (Zhong et al., 2019). When accounting for springtime warming rates, the resulting effect was more pronounced in Lake Ontario, increasing with water depth and comparable to the summertime warming rates for Lake Superior (Toffolon et al., 2020; Zhong et al., 2019).

One of the most alarming effects of climate-driven warming LSWT and decreasing lake ice cover is alterations of lake mixing regimes (Figure 2.1). For dimitic lakes (lakes that experience two mixing events per year during summer and autumn), warmer winter LSWT and loss of lake ice cover causes lakes to no longer experience inversed stratification (ice on the top layer, warmest and densest 4°C water at the bottom). As a result, these lakes remain vertically mixed from autumn to spring, changing from dimitic to monomictic conditions (Woolway & Merchant, 2019). If LSWT keeps warming up and no longer falls to 4°C, thermal stratification can continue year-round, preventing any mixing from taking place. This subsequently changes monomictic lakes to oligomictic (persistently stratified, occasionally mixed) and/or meromictic (permanently stratified) conditions (Woolway et al., 2019; Woolway et al., 2020). Woolway & Merchant (2019) analyzed the mixing regimes of 635 lakes worldwide and predicted that one-sixth of currently dimictic lakes would become monomictic, and all currently oligomictic lakes will become meromictic by the end of this century.

Wind speed is another important factor that can cause significant changes in lake mixing regimes. Reduced wind speed reduces the amount of energy available to mix warmer waters at the surface (epilimnion) to bottom (hypolimnion) layers, thus strengthening thermal stratification (Siver et al., 2018; Woolway et al., 2017). However, an increase in wind speed could cause continuous periods of mixing, transitioning lakes from dimictic to polymictic conditions. This effect is especially most pronounced in shallow lakes (Woolway & Merchant, 2019). There are also many other factors that could influence lake mixing regimes, such as water clarity (Shatwell et al., 2019), surface area and depth (Gorham & Boyce, 1989), and inflows (Peter & Sommaruga, 2017; Valerio et al., 2015).

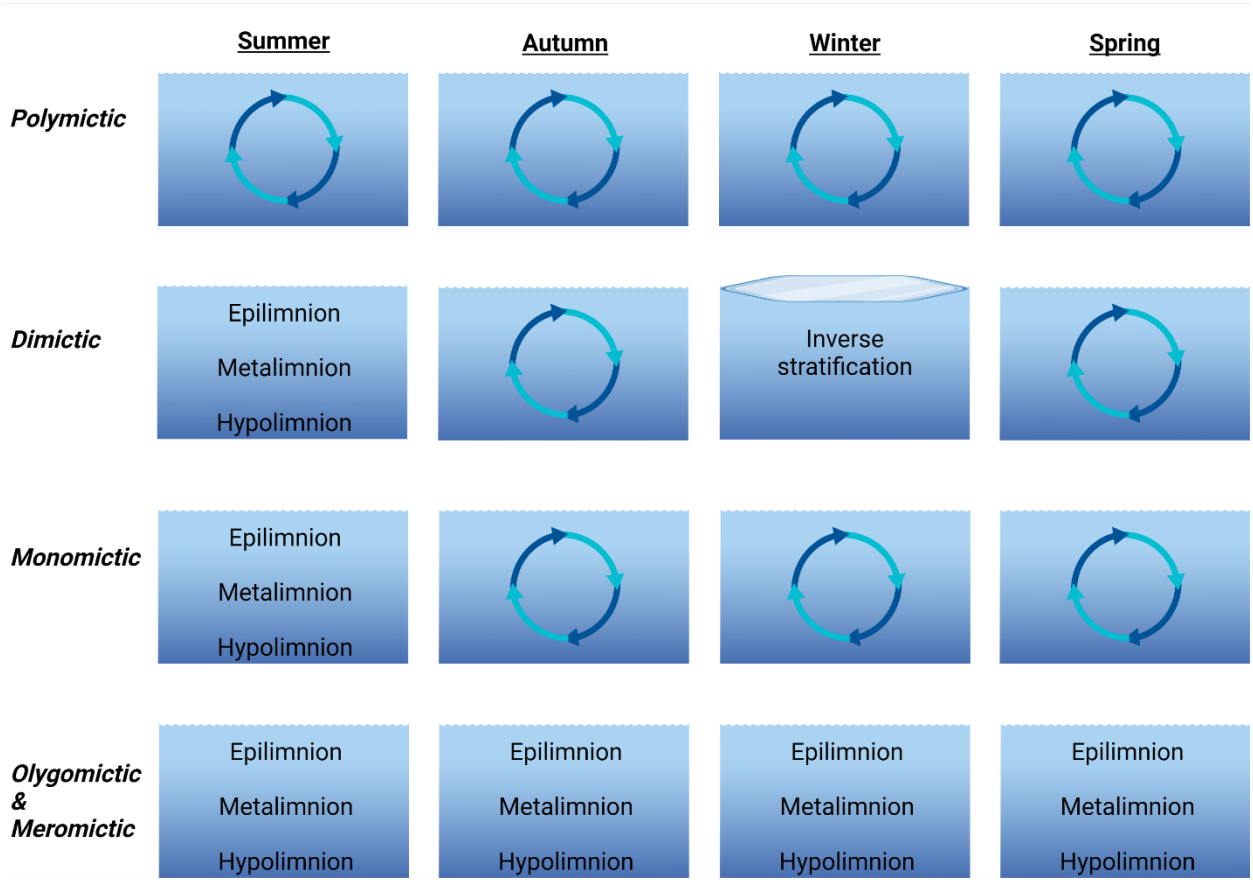

Figure 2.1. Lake mixing regimes. Created with BioRender.com.

With increasing LSWT and prolonged thermal stratification projected for lakes globally, deoxygenation of bottom waters is projected to become a serious problem. A lack of vertical mixing will lead to a decrease in oxygen concentrations in the hypolimnion and can lead to the formation of deep-water hypoxia zones (North et al., 2013). Warmer water temperatures reduce the solubility of oxygen, and at the same time increase primary production in the photic zone. This causes rapid oxygen depletion through the decomposition of dead organisms that settle to lake bottom, as well as high respiration rates by both producers and consumers during nighttime (Collingsworth et al., 2017).

Jane et al. (2021) analyzed 45,148 dissolved oxygen and temperature profiles of 393 temperate lakes from 1941 to 2017 and discovered that dissolved oxygen depletion was widespread in both surface and deep-water habitats. Alarmingly, deoxygenation in freshwaters is 2.75-9.3 times greater than that in the oceans. In the Laurentian Great Lakes, Lake Erie has been facing hypoxia since 1929 (Charlton, 1980). Since the mid-1990s, the frequency of hypoxia has increased, and this has been attributed to both eutrophication – which leads to algal blooms – and extended thermal stratification (Perello et al., 2017). Lake Michigan has also experienced hypoxic conditions since the mid 20th century, with increased frequency in recent years (Val et al., 2018).

Climate change also influences lakes by shifting the precipitation patterns, increasing evapotranspiration and glacier retreats, thus changing lake water storage balance (Woolway et al., 2020). The outcomes differ globally depending on numerous factors, but the common paradigm is that ‘dry gets drier, wet gets wetter’ (Woolway et al., 2020). For example, increasing temperature, decreasing precipitation, together with water mismanagement are projected to intensify drought in Iran in upcoming years (Ahmadaali et al., 2018; Khalilian & Shahvari,

2019). The Laurentian Great Lakes region has seen an increase in evapotranspiration correlating with an increase in annual temperature, resulting in a decrease in streamflow and run-off (International Joint Commission, 2003). However, water levels across the Great Lakes have risen in recent years, driven by weather extremes and climate variability. In 2013, after an extended period of record low levels, Lakes Superior and Michigan-Huron began the transition to high water level conditions (Gronewold & Rood, 2019). In May 2017, water levels on Lake Ontario rose to a then-record high of 75.69 metres, resulting in widespread flooding. By July 2019, water levels reached the average level of 75.82 metres (Joseph, 2019). This unusual high level of water presents many challenges for Lake Ontario management, especially in term of flood control and waterway safety (Baldwin, 2019).

Overall, the impacts of climate change on lakes are complicated, driven by many factors that are interconnected with each other (Smith et al., 2019; Woolway et al., 2020). These drivers also have major implications for lake ecosystems. Shortened ice coverage, increasing stratification and elevated nutrient loading have been linked to increasing cyanobacterial blooms (Favot et al., 2019). Interestingly, episodic wind events have been found to help sustain algal blooms by deepening the epilimnion and entraining internally loaded nutrients (Weinke & Biddanda, 2019). Changes in lakes physical and chemical properties also lead to changes in phytoplankton community biomass and composition (da Silva et al., 2019; Urrutia-Cordero et al., 2017), which subsequently alters lake food webs (Collingsworth et al., 2017; Woolway et al., 2020). The changes in the food webs are also associated with the climate-change-induced spread of invasive aquatic species and reduction of habitat availability for cold-water fish species (Mason et al., 2016). As these stressors are all linked and interact with each other either directly or indirectly (Collingsworth et al., 2017; Smith et al., 2019), it is more important than ever to

broaden our understanding on climate change impacts on lake ecosystems to better manage current lakes and predict future changes. As lakes are very sensitive and respond quickly to climate changes (Adrian et al., 2009), and climate has always fluctuated in the past, looking at past changes can provide valuable insights into how lacustrine ecosystems respond to climate change.

2.2 Past Climatic Fluctuations in Southern Ontario over the Holocene

The Holocene is the most recent epoch of Earth history, which begins at the last glacier retreat and extends to the present day (Walker et al., 2009). The Canadian Shield – including the entire Great Lakes basin – was covered by the Laurentide Ice Sheet, which together with the Cordilleran Ice Sheet and the Innuitian Ice Sheet made up the Late Wisconsinan North American ice sheet complex. The Laurentide Ice Sheet reached its maximum volume just before approximately 20 ka BP before it started to retreat rapidly beginning at 16 ka BP (Dyke, 2004). By the time of around 13 ka BP, at the last stage of the Late Wisconsin glaciation, the Oak Ridges Moraine – southern Ontario's largest glacial landform – had formed between converging paleo ice streams within the last Laurentide Ice Sheet (Sookhan et al., 2018).

There were several paleoclimate studies available in the Northeastern America region. Using fossil pollen data and the pollen response surfaces (nonlinear functions of each taxon's expected abundance with different environmental variables) from 60 sites across the Northeast, Webb et al. (1993) estimated that the region experienced droughts from 12 ka BP to 6 ka BP, with peak dry conditions at 9 ka BP. From 6 ka BP to 3 ka BP, a major shift in annual precipitation occurred, changing the regions to much moister conditions. Liefer and Shuman (2020) placed the shift to wetter climate in the region slightly earlier at about 7 ka BP using

synthesized sedimentological and geomorphic evidence of water level changes from 173 lakes across North America.

Holocene climate in southern Ontario is quite different than that of northeastern America. A combination of oxygen isotope ($\delta^{18}O$), sediment hiatuses, detritus layers, and inwashed terrestrial moss layers from Crawford Lake were used by Yu et al. (1997) to reconstruct past climate. The results of this study showed that the region was wetter and cooler from about 10 ka BP to 4.8 ka BP, before transforming to a dry and warm climate lasting from 5-4.8 ka BP to 2 ka BP. Another earlier study using pollen analysis by Yu and McAndrews (1994) discovered that Rice Lake underwent a long period of shoreline transgression from at least 10 ka BP to approximately 6.0 ka BP, followed by a warm period between 6 and 4-3 ka BP, with mean July temperatures about 1°C higher and annual precipitation about 10% less than before and after this period. This result was similar to a later study by Sonnenburg et al. (2012) using a digital elevation and bathymetric model, however they found that Yu & McAndrews underestimated the water depths between 12 and 6 ka BP due to uncompensated isostatic effects. Liefer and Shuman (2020) also put the dry and warm period in the region between 6 and 3 ka BP, with minimum lake level at approximately 3 ka BP.

The difference in speculated timing of the warm and dry period between Yu et al. (1997) and the other studies might be due to regional variations, as Crawford Lake is further south and west than Rice Lake. Generally, despite significant regional variations, the early and mid-Holocene southern Ontario enjoyed a mesic (moderate or well-balanced supply of moisture) climate, before changing to a more xeric (dry) conditions in the mid and late Holocene – corresponding to the mid-Holocene Hypsithermal, and then reversing back to more mesic conditions by late Holocene approximately 3-2 ka BP. This contrasts with the moisture regime

reconstructions of northeastern America but appears to be more similar to the trends in in midwestern North America, implying that the Holocene paleoclimate in southern Ontario was probably more connected with the Midwest than the northeast (Yu et al., 1997). Mid-continental North America experienced a megadrought about 4.1-4.3 ka BP (Booth et al., 2005), which coincided with the reported dry period in southern Ontario.

Much less is known about past regional variations in Holocene climate north of the Oak Ridges Moraine, with only few published studies on the Kawartha Lakes and the nearby Rice Lake (Conolly, 2020). Using predictive models of hydrological flow, sedimentation and isostatic rebound at five representative periods (12.0 ka BP, 8.0 ka BP, 4.0 ka BP, 2.0 ka BP, 200 BP) for Kawartha Lakes, Conolly (2020) suggested that the region also experienced a drought period between 6-3 ka BP. The area shifted to cooler and wetter periods at ~3.0 ka cal BP, with precipitation and lake levels returned to modern day rates by 2.0 ka cal BP. In another study, Watchorn et al. (2008) reconstructed significant alterations in the biological community composition through the last ~400 years in Swan Lake (a small kettle lake located on the Oak Ridges Moraine) but did not find any significant correlation between temperature and diatom compositions. The study however noted that the general warmer regional trend of the last century (~1.3°C increase in air temperature) was not presently enough to change the biology of Swan Lake, partly due to proximity to large urban center (Toronto). It is evident that within the Kawartha Lakes region, paleoclimate records are still very far and few between, with low resolutions and vary between different locations. A high-resolution paleoclimate record of Holocene paleoclimate for the Lake Scugog basin would contribute new insights to our understanding of post-glacial environmental change in the region.

Table 2.1. Summary of suggested Holocene climate periods in Northeastern America, Southern Ontario and Kawartha Lakes regions:

Northeastern America	**Southern Ontario**	**Kawartha Lakes region**
Webb et al. (1993): • 12-6 ka BP – warm, dry conditions (peak dry conditions at 9 ka BP) • 6-3 ka BP – cool, wet conditions Liefer & Shuman (2020): • 12-7k BP – warm, dry conditions • 7k BP – shift to cool, wet conditions	Yu et al. (1997): • 10-4.8 ka BP – cool, wet conditions • 5/4.8-2 ka BP – warm, dry conditions Liefert & Shuman (2020), Sonnenburg et al., (2012); Yu & McAndrews (1994): • 6-4/3k BP – warm, dry conditions (mid-Holocene Hypsithermal) • Minimum water level at ~3k BP (Liefert & Shuman, 2020)	Conolly (2020): • 6-3 ka BP – warm, dry period • 3 ka BP – shift to cool, wet conditions • 2 ka BP – return to modern precipitation rates

2.3 Paleolimnology

There are many techniques that are employed to reconstruct paleoclimate such as studies of ice core, tree rings, coral remains, speleothems among others (DeLong et al., 2013; Verheyden et al., 2008; Yang et al., 2009), but paleolimnology remains one of the most popular methods, and the best approach to paleoclimate reconstruction of Lake Scugog. Paleolimnology is a multidisciplinary science that uses various physical, chemical, and biological information preserved in lake sediments to interpret and reconstruct the past climates, limnological processes and conditions in lake basins. These proxies can come from both autochthonous (internal) and allochthonous (external) sources, such as catchment, groundwater and the atmosphere (Last & Smol, 2001). By analyzing these indicators, it is possible to reconstruct not only the past aquatic conditions of Lake Scugog, but also the past terrestrial conditions in the watershed.

Retrieving a sediment core that represents a reliable stratigraphic record for analysis is the first and most important step in a paleolimnological study. There are numerous methods to collect and extrude sediment cores, all of which require precise techniques and attention (Glew et al., 2001). After being retrieved, sediment cores can be dated using many available geochemical indicators to establish a chronology, which is essential to interpretation of information stored in the cores. ^{210}Pb dating is the most common method for recent sediments of the last ~150 years (Appleby et al., 1986), and ^{14}C dating is often applied for much older sediments back to ~40,000 years as oppose to last few hundred years due to the fairly large measuring uncertainties, varying atmospheric ^{14}C content, combustion of fossil fuels and nuclear weapon tests (Björck & Wohlfarth, 2001). The key assumption for any relative age dating is that more recent sediments overlie older materials – also called the Law of Superposition (Barker, 2009).

One of the most common non-biological proxies in paleolimnology is stable isotopes. Isotopes are atoms of the same element (having the same number of protons) that differ in the number of neutrons (Kendall & Doctor, 2003). Stable oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) isotopes are often used in reconstruction of past climate, as their compositions in precipitation are highly controlled by temperature and moisture sources. On the other hand, stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes are often in reconstruction of past aquatic food web processes (Pienitz et al., 2009).

Biogenic silica (BSi) – one of the most widespread biogenic (product made by a life form) minerals on Earth – is another common proxy in sediments. BSi can come from various sources such as diatoms, phytoliths and sponge spicules (Zhang et al., 2016). As a single proxy, BSi provides an index of both diatom abundance and productivity, as well as of other siliceous microfossils sponges and phytoliths (Conley & Schelske, 2001), and when combined with isotope analysis, BSi can be a useful tool to study climate change and environmental processes (Conley & Schelske, 2001; Leng & Sloane, 2008).

Industrial combustions of non-gaseous fossil-fuels produce an unnatural proxy known as fly-ash. Fly-ash is a combination of matters that were formed during the combustion process, non-combustible inorganic ash spheres, and most importantly, combustible spheroidal carbonaceous particles (SCPs) that were not completely burned (Rose, 2001). As SCPs are not of natural sources, they become an unambiguous marker of anthropogenic impacts, specifically on a regional level due to high levels of variations on larger scales. The use of SCPs as a dating marker will become increasingly important in the future, due to ^{210}Pb dating gradually decreases its accuracy with sediments from late-19th century and progressively successive periods (Rose,

2001). Accumulations of SCPs are also often collaborated with other contaminants in sediments to assess the extent of pollution and human impacts (Barst et al., 2017; Rose, 2001).

The compositions, texture and properties of sediment particles can give valuable paleoenvironmental information. Mineralogical analysis of sediments can provide information on the tectonic and weathering processes of the watershed, or sediment origin and transportation (Last, 2001). Fluid inclusions (bubbles filled with liquids trapped within crystals) analysis of crystals in sediments can give clues to the temperature and chemical compositions of water at the time of formation (Lowenstein & Brennan, 2001). Magnetic properties of sediment particles can also assist to a wide range of studies – from physical processes in the lake basin to the Earth's magnetic field (Sandgren & Snowball, 2001).

There are many biological proxies – both terrestrial and aquatic. For terrestrial proxies, pollen and spores are perhaps the most popular. While spores are commonly found in ferns and mosses, pollen grains are found in angiosperms and gymnosperms. They are plant parts that are produced in anthers, containing a male nucleus for fertilization. The pollen data reflects not only inputs from local plants, but also a regional component of airborne or stream-borne pollen (Bennett & Willis, 2001). As vegetation can synchronously respond to abrupt climate changes, records of vegetation change preserved in pollen time series have been used to examine climate variability on different spatial and temporal scales (Gajewski & Viau, 2011). Pollen can also be used as an independent dating marker since a rise in *Ambrosia* pollen following widespread deforestation for agriculture signals the time of European settlement (Brugam, 1978; Van Zant et al., 1979).

Phytolith is a relatively new but becoming increasingly popular terrestrial proxy for paleoenvironmental study. Phytoliths are formed when soluble silica in groundwater is absorbed

through the roots, carried out through its vascular system and deposited within the cellular structure of a plant (Piperno, 2001). While a single plant can have several distinct phytolith morphotypes depending on the portion of the plant, in general, phytoliths can be used for precise identification down to genus, or sometimes even species level (Nurse et al., 2017; Piperno, 2001). Combination of phytolith and pollen data sets are common in paleoenvironmental studies, providing better insights into ecosystem turnover, as each proxy is more sensitive to different floristic changes (Plumpton et al., 2019).

There are many other terrestrial proxies including but not limit to charcoal, conifer stomata, plant macrofossils, among others. Charcoal – the product of incompletely combusted organic matter – can be used to reconstruct fire history, complimenting with dendrochronological and historical records (Whitlock & Larsen, 2001). Both conifer stomata and plant macrofossils are not prone to long distance transport, therefore are more suited for reconstruction of local vegetation (Birks, 2001; Macdonald, 2001). Plant macrofossils also provide material for ^{14}C dating, thus hold great importance especially for older sediments (Birks, 2001).

While terrestrial proxies can give information on regional climatic and terrestrial processes, it is the aquatic proxies that can provide direct information on both climate and the waterbodies of interest. Aquatic proxies can range from large remains of fish – an indicator of not only living but also death conditions (Patterson & Smith, 2001), freshwater molluscs shells – abundant in calcareous waters and exhibit high accumulation of many pollutants (Lau et al., 1998; Miller & Tevesz, 2001) to microscopic ostracods (subphylum Crustacea, class Ostracoda), commonly known as seed shrimp – also typical of alkaline waters and can track a wide range of environmental variables (D'Ambrosio et al., 2017; Holmes, 2001).

Fossil remains of the larval stages of insects are frequently used in paleolimnological studies. A wide range of insects have been used as environmental indicators such as biting midges – ceratopogonids (order Diptera, family Ceratopogonidae), mayflies – ephemeropterans (class Insecta, order Ephemeroptera), caddisflies – trichopterans (class Insecta, order Trichoptera), oribatid mites (subclass Acarina, order Oribatida). However, they are still understudied in paleolimnology due to their rarity, difficulty in preservation and identification, or inadequate autecology (Luoto, 2009).

Among insects, the larval fossils of true flies (order Diptera) are the most common and within this group, non-biting midges, also known as chironomids (family Chironomidae), is the most abundant in lake sediments (Walker, 2001). Diverse groups of chironomids can be identified through their chitinous head capsules that are well preserved and widely distributed in lake sediments (Brodersen & Quinland, 2006). Chironomid larvae have been used as indicators for lake productivity and hypolimnetic oxygen conditions since the 1920's, however they only truly gained popularity since the 1980's and 1990's (Walker, 2001). Chironomids are also valuable indicators of lake temperature, water depth, pH (Walker, 2001), and can be used to build inference models for paleoclimatic conditions at a regional scale (Brooks, 2006).

Water fleas, also known as cladocerans (class Branchiopoda, order Cladocera), are primarily freshwater microcrustaceans that live in almost any kind of aquatic or semi-aquatic habitats, from the largest lakes to water-filled moss growing on trees in rain forests (Korhola & Rautio, 2001). This is an ancient group originated from the mid-Paleozoic era, and unambiguous fossils are known starting from the Mesozoic era, specifically the Early Jurassic period (Forró et al., 2008; Kotov, 2007). Cladoceran body parts such as head shields, mandibles, post-abdominal claws, as well as their hard egg cases are commonly preserved in lake sediments (Korhola &

Rautio, 2001). They have been used as indicators of various environmental changes such as water level, pH, lake trophic status, food web as well as climate change (Korhola & Rautio, 2001). Cladocerans, together with chironomids, made up the most commonly used group of invertebrate remains in paleolimnology (Luoto, 2009).

Overall, there are many distinctive proxies that are excellent indicators of different environmental processes in paleoenvironmental research. But for this study, the proxy of choice was diatoms. Diatoms (class Bacillariophyceae) are unicellular microalgae with well-preserved silica cell walls, widely distributed and abundant in both fresh and marine water, and even moist terrestrial environments that have sufficient light for photosynthesis (Moser, 2004). They are another ancient group, of which earliest known fossils are dated back to the Late Jurassic (Girard et al., 2020). The diatom assemblages can be indications of numerous environmental variables such as pH, salinity, eutrophication, water level, turbulence etc. and have been commonly used to examine past limnological conditions and climatic changes (Battarbee et al., 2001).

2.4 Diatoms as Paleoecological Indicators

Diatoms are characterized by their unique silica cell walls called frustules which are made up of two overlapping halves called thecae. Each theca consists of a valve held together by a fragile band (girdle). Nearly all diatoms have fine pores (areolae) on the cell walls – these simple perforations can appear as continuous lines (striae), forming distinct pattern for each species (Battarbee et al., 2001). Based on the shape of the frustules (Figure 2.2; Figure 2.3), there are two main groups of diatoms: centric diatoms – characterized by radial symmetry, and pennate diatoms – characterized by bilateral symmetry (Almqvist et al., 2001). Most pennate diatoms possess an elongated slit, or a pair of fissures in the valve called the raphe. Its type (e.g. naviculoid or canal), presence or absence help further categorize pennate diatoms into smaller

groups (Battarbee et al., 2001). Since the silica walls do not undergo decomposition, they are well preserved in the sediment. The shape, size and ornamentation of the valves are crucial for an exact identification down to species level (Battarbee et al., 2001; Jalba et al., 2005).

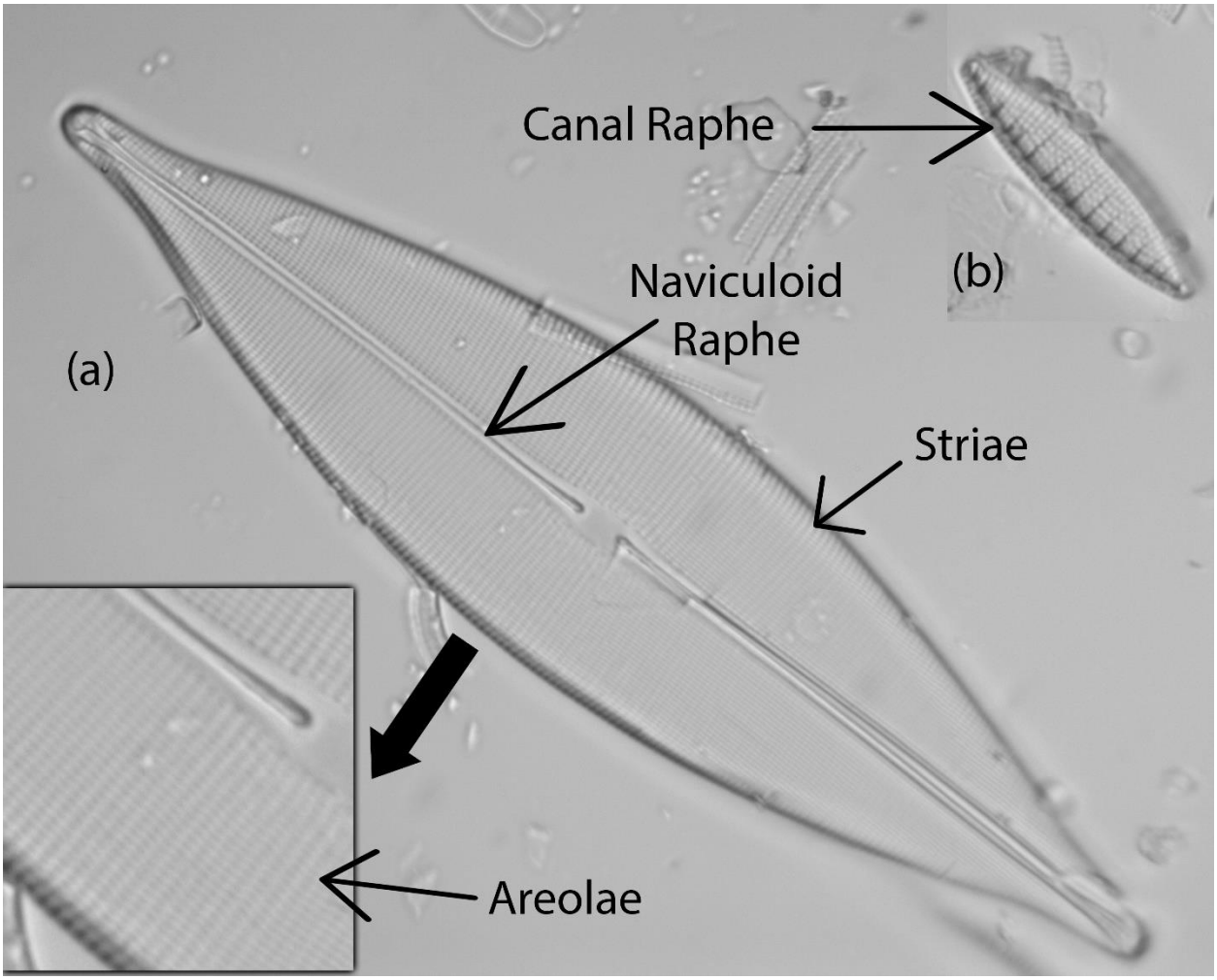

Figure 2.2. Important features of pennate diatom frustules: The striae (consisting of rows of areolae) and the raphe. The more common naviculoid raphe runs along the central axis of the valve, while the canal raphe runs along the margin of the valve. Pictured: (a) *Navicula cuspidata*, (b) *Nitzschia amphibia*.

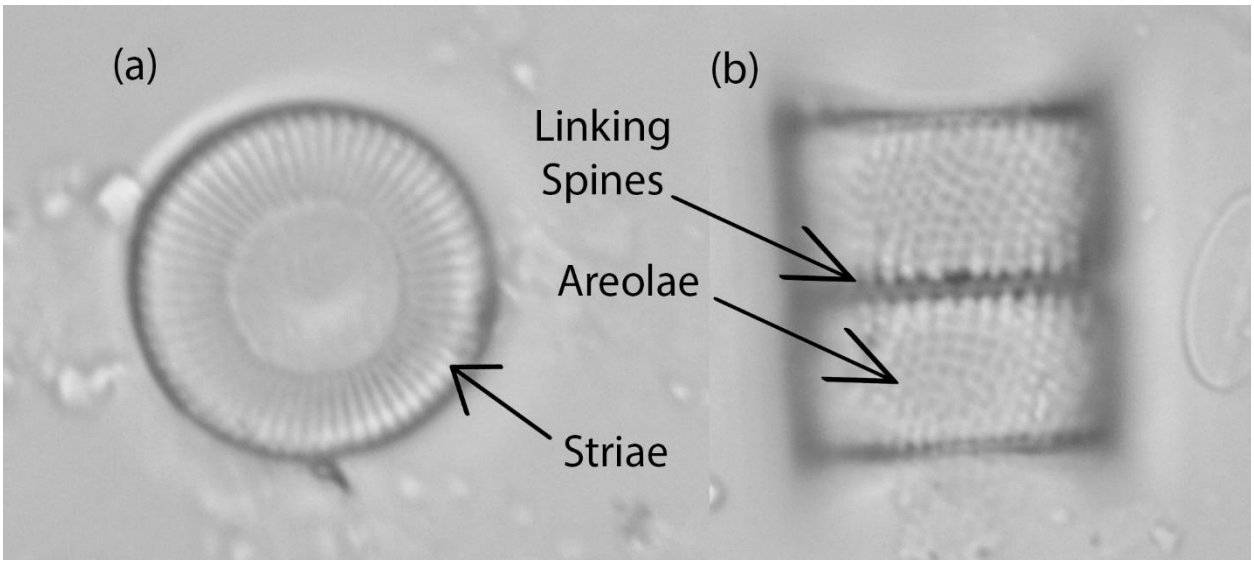

Figure 2.3. Important features of centric diatom frustules: The striae, the areolae and the linking spines. Pictured: (a) *Cyclotella distinguenda*, (b) *Aulacoisera ambigua*.

Diatoms are widely distributed worldwide in both freshwater and marine environments, with an estimation of about 100,000 extant species (Mann & Vanormelingen, 2013). They contribute approximately 20% of the Earth's total primary production, including 40% of the total marine primary production and play an important role in the biological carbon pump (Tréguer et al., 2018). There can be found both very tolerant species with a wide range of ecological tolerance, and very tenacious species with narrow and distinct environmental requirements. Their short lifespans and rapid reproduction help them respond quickly to environmental changes, especially those driven by intense anthropogenic landscape modification and post-industrial climate warming (Battarbee et al., 2001). Overall, their abundance, diversity in ecological niches and quick response rate make diatoms an excellent proxy to reconstruct past limnological and climatic changes.

In lakes, diatoms can be found colonizing both benthic and planktonic habitats. The plankton can spend a part of (meroplankton), or their entire life cycle suspended in the water

column. On the other hand, the benthos are associated with substrates such as mud (epipelic), stones (epilithic) and aquatic plants (epiphytic) around the margins of lakes. Notably, some taxa are benthic, but can also be found in planktonic habitat under certain conditions (tychoplankton or pseudoplankton) (Battarbee et al., 2001). Most diatoms are solitary; however, many taxa can form colonies that vary in shape and size (Figure 2.4). Some taxa such as *Aulacoisera* and *Fragilaria* can form chain colonies linked together by spines, while other taxa such as *Tabellaria* can form star-shaped, zigzag or coiled colonies linked together by muco-polysaccharide strands or pads (Battarbee et al., 2001).

The benthic-planktonic ratio can be used to infer past water depths. Specifically, a decline in lake level will result in a relative increase in benthic taxa as well as a decrease in planktonic diatoms, suggesting a shallower lake and vice versa (Haig et al., 2013; Laird et al., 2011). Changes in diatom assemblages can also help detecting an increase in LWST associated with climate warming. In subarctic and temperate lakes, small, planktonic cyclotelloid diatoms becoming dominant over heavier, tychoplanktonic diatoms that rely on strong turbulence in water columns to stay in the photic zone is a signal that the lake is becoming more stratified. Whilst in High Arctic lakes, diatom assemblages can shift from predominantly benthic fragilarioid species (family Fragilariaceae) to a more complex and diverse assemblages of periphytic diatom as a respond to habitat expansion and longer growing season resulting from decreasing ice cover (Rühland et al., 2015).

As many diatom taxa show clear preferences on pH, trophic status and salinity, diatoms have long been used as sensitive indicators of those environmental variables (Van Dam et al., 1994). Diatoms have been used as eutrophication indicators since the beginning of the 20th century, however, they only became a primary tool starting from the 1970s (Battarbee et al.,

2001). During the 1980s, as concerns about acid rain became publicly widespread, diatoms have also been used to reconstruct surface water acidification in lakes across Europe and North America (Schindler, 1988). And in recent years, as salinity increase caused by de-icing road salts becoming a growing threat to freshwater lakes, halophilic diatom taxa have been proven to be invaluable in tracking salinity/conductivity (Ginn et al., 2015; Oškinis & Kasperovičius, 2005).

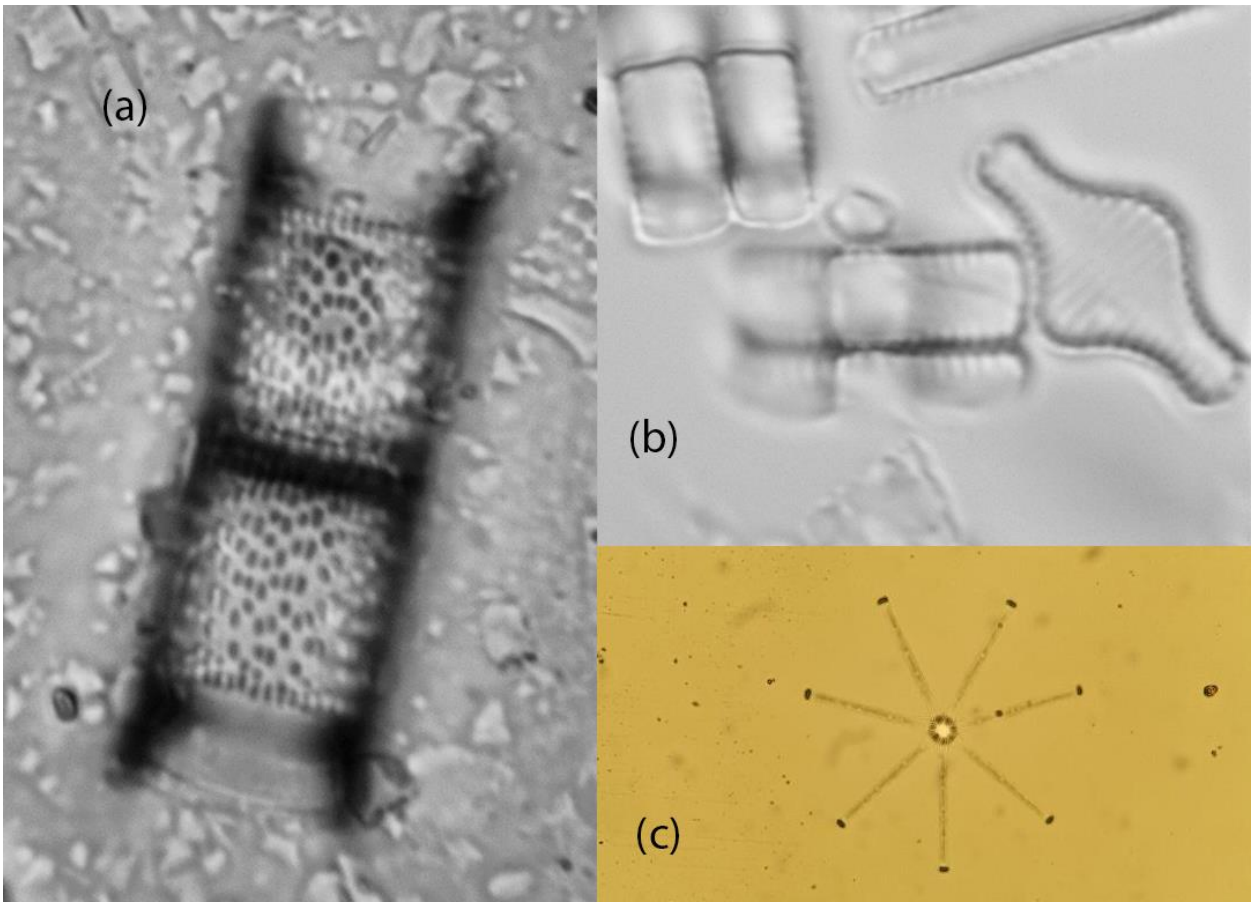

Figure 2.4. Various forms of diatom colonies: chain colonies linked together by spines (a, b), star-shaped colony (c). Pictured: (a) *Aulacoisera crenulata*, (b) *Fragilaria construens* (in both colony and solitary forms), (c) *Asterionella formosa* (taken under a dissection microscope).

CHAPTER THREE: STUDY SITE DESCRIPTION

3.1 Lake Scugog Geological Setting

The Lake Scugog basin was formed following the retreat of the Laurentide ice sheet ~12,000 years ago (Fisher & Alexander, 1993). The present-day Lake Scugog (located in the regional municipalities of Durham and Kawartha Lakes, Ontario) is a large (68 km^2 in surface area) and shallow (maximum depth = 7.6 m, mean depth = 1.4 m) impoundment located just north of the Oak Ridges Moraine. It is a headwater lake in the greater Kawartha Lakes system (Kawartha Conservation, 2010), and has been classified as a shallow, polymictic, eutrophic lake, dominated by macrophytes (Harrow-Lyle & Kirkwood, 2020a).

The Lake Scugog watershed covers 529.7 km^2 (Kawartha Conservation, 2010), topographically slopes from south to north, overlying a bedrock made up of mostly limestone and shale (Kawartha Conservation, 2012). Lake Scugog is a marl lake – defined as a highly alkaline, carbonate-rich lake in which the concentration of dissolved calcium carbonate ($CaCO_3$) is over 100 mg/L, and over 60% of lake sediment dry weight (Pentecost, 2009).

Lake Scugog receives water from many sources within the watershed. The Nonquon River and Blackstock Creek are the largest tributaries into the lake. Other tributaries include Cawker's Creek, William's (Jesters) Creek, Fingerboard Creek and many other small, unnamed watercourses (Kawartha Conservation, 2010). The Scugog River, located in the northeastern corner, is the only outflow from the lake, carrying water northward through the Lindsay Dam and emptying into Sturgeon Lake. Water levels in Lake Scugog are presently managed by the Trent Severn Waterway operations at the Lindsay Dam and are highly sensitive to climatic fluctuations. Seasonal lake water level fluctuations on the lake usually range between 20 and 50

cm (Kawartha Conservation, 2010). While offshore lake water temperatures tend to be stable (Harrow-Lyle & Kirkwood, 2020a), nearshore lake water temperatures also fluctuate, with reports of water temperatures being 25˚C or higher in late summer (Smith & Kirkwood, 2020)

Lake Scugog consists of two elongated west and east basins (Figure 3.1). Each basin has very different ecohydrological regimes and hydrographic features. The west basin has more extensive shoreline development and shallow water depths, with maximum depth ~2.5 m near the town of Port Perry (Kawartha Conservation, 2013). It receives high nutrient loading from the Nonquon River and urban run-off from Port Perry which results in abundant aquatic vegetation (Kawartha Conservation, 2010). During a four-year monitoring program (2016-2019) of Ontario Tech University by Harrow-Lyle and Kirkwood (2020a), total phosphorus (TP) concentrations were measured to be approximately 50 µg/L on average but could reach up to ~320 µg/L. The average total nitrogen (TN) concentration was about 0.5 µg/L, values close to 4 µg/L were also recorded. Chloride concentrations were higher in the west basin, with the highest chloride levels of nearly 500 mg/L measured in the Port Perry Bay era (Harrow-Lyle & Kirkwood, 2020a).

The east basin is generally deeper than the west basin (maximum depth ~7.6 m), and while it receives less nutrient loading compared to the west side, there is still a considerable amount of macrophytes present in the shallower areas (Kawartha Conservation, 2010). Harrow-Lyle & Kirkwood (2020a) found that while the average TP concentration in the east basin was much less than in the west basin at approximately 25 µg/L, it could still reach near 350 µg/L. TN concentrations generally were similar to the west basin but could get up to ~7 µg/L. Chloride concentrations were considerably lower, with the highest values of ~350 mg/L. Despite being polymictic, the east basin was also found to be experiencing periodic thermal stratification even during the ice-free season (Harrow-Lyle & Kirkwood, 2020a).

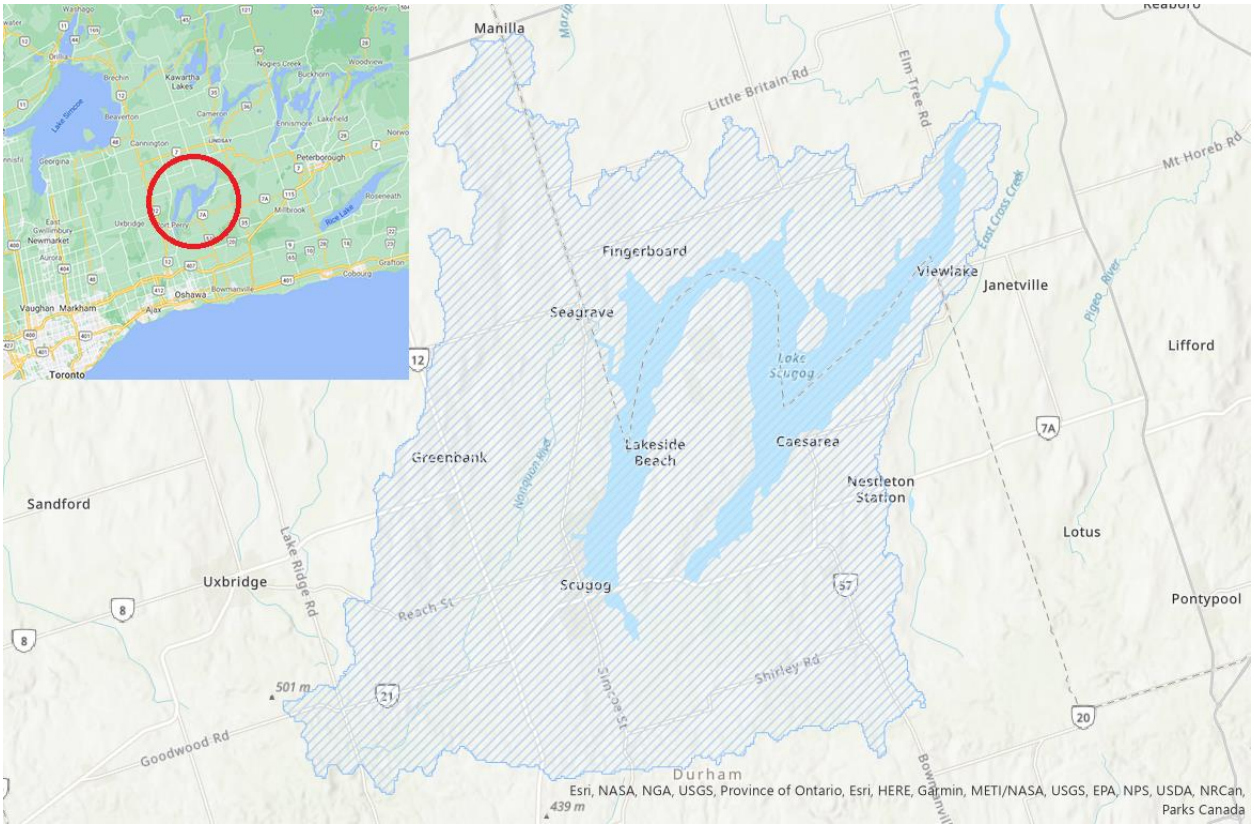

Figure 3.1. Map of Lake Scugog and its watershed.

3.2 Lake History

Lake Scugog was a marsh when the first Mississauga people settled in the Lake Scugog basin at around 1700 (Mississaugas of Scugog Island First Nation, n.d.). The current Lake Scugog was created following the construction of the Lindsay Dam in 1837 shortly after European colonization, which caused a four-foot rise in water levels and made the lake part of a navigable waterway (Kawartha Conservation, 2010). Not much is known about the hydrological history of the Lake Scugog basin prior to this, but historical records from the Mississauga First Nations describe extensive wetlands that were rich in fish, waterfowl, and wild rice (*Zizania aquatica*) (Mississaugas of Scugog Island First Nation, n.d.).

Since the creation of the dam, water levels in Lake Scugog have been a controversial topic. While many people enjoyed new opportunities like fishing and transportation, a lot of farmers were outraged at the loss of farmland (Kawartha Conservation, 2010). Shortly after the construction of the Lindsay gristmill dam by William Purdy, in summer 1838, the stagnant water of the lake caused a wave of deadly plague of fever and ague that killed off settlers on the farms nearby. Angry grieving local residents rose up and tore the dam apart, lowering the lake water level once more. After Purdy struck an agreement with the Board of Works of the Province of Canada, the dam was rebuilt by the government in its current location, and was finally completed in 1844 (Canadian Genealogy, n.d.).

The town of Port Perry (southwestern Lake Scugog) was established in the early 19th century and has since became the largest urban center in the predominantly rural Lake Scugog basin, with a population of over 9,400 as of 2016 (Statistics Canada, 2016). While overall the watershed is not densely populated (urban areas accounting for only over 3.5% of the watershed land), over 40% of Lake Scugog shoreline has been developed, including many residential zones along the shorelines. Approximately 53% of the total area of the watershed is also used in some form of agriculture (Kawartha Conservation, 2010).

The present-day Lake Scugog is facing a lot of modern problems that cause many heated debates between local residents and lake managers, including issues related to water quality and ecosystem degradation, invasive species, water level management, and fisheries management. These problems are influenced by both climate change and intense development, posing numerous challenges for lake managers (Kawartha Conservation, 2010). These issues are not only affected by urban development – especially near shoreline zone – but also by climate change (Smith & Kirkwood, 2020). A deeper understanding of how the lake is responding to

multiple stressors is needed to guide stakeholders in developing adaptation and mitigation strategies with regards to regional hydrological and ecological shifts that might be expected with future climate change.

3.3 Lake Management Challenges

3.3.1 Eutrophication

Eutrophication has been one of the biggest concerns in Lake Scugog since the 1970s (Kawartha Conservation, 2010). In eutrophic conditions, excessive production of plant and algal biomass can result in hypolimnetic oxygen depletion and subsequent fish kills as a result of high respiration rates from the decomposition of dead and decaying organic matter (Padedda et al., 2017). Algal and cyanobacteria (blue-green algae) blooms also have the potential to release toxins (e.g. microcystin, saxitoxin) that may be harmful to humans, pets and livestock that come in contact with the water through swimming, fishing or drinking (Backer et al., 2015).

During the 2016-2019 Ontario Tech University monitoring program by Harrow-Lyle and Kirkwood (2020a), wide-spread phytoplankton (predominantly *Microcystis*) blooms were recorded for the first time in recent history (though lake managers have not conducted prior monitoring for algal blooms). In July 2017, the Region of Durham Public Health issued an advisory regarding a blue-green algae bloom that was reported in Lake Scugog at a beach in Port Perry (“Blue-green algae toxin levels in Port Perry intensify, provincial tests show,” 2017). The algal blooms persisted and progressively worsened over the course of the monitoring program (Harrow-Lyle & Kirkwood, 2020a), and a second warning was issued in August 2020 (“Public urged to 'avoid contact' with Lake Scugog water after blue-green algae discovered at Port Perry beach”, 2020).

The most important factor controlling the occurrence and persistence of algal blooms in lakes is nutrient loading (both nitrogen and phosphorus). Phosphorus (P) and nitrogen (N) are basic building blocks of DNA and RNA, and also needed for energy transfer and protein synthesis (Conley et al., 2009). While P has long been considered the primary limiting nutrient in freshwater primary production, the importance of N in controlling algal blooms has been intensely debated (Conley et al., 2009; Paerl et al., 2014). N in particular is a major controlling factor of *Microcystis* blooms, as the members of this genus cannot fix N_2 from the atmosphere and require a combination of both natural and anthropogenic N sources such as agricultural/urban run-off and atmospheric deposition (Paerl et al., 2014). Every year, TN loading in Lake Scugog reaches approximately 340 to 390 tonnes, coming mostly from the tributaries (contributing over 60% of TN), as well as atmospheric deposition (over 20% of TN), direct urban run-off, septic systems and discharges from the Nonquon River Water Pollution Control Plant (Kawartha Conservation, 2010). From 2004 to 2008, TN concentrations showed a general decreasing trend (Kawartha Conservation, 2010), and from 2016 to 2019, Harrow-Lyle and Kirkwood (2020a) found the TN concentrations to be stable. Interestingly, Harrow-Lyle and Kirkwood also did not find N to be a key driver of algal blooms in Lake Scugog.

Kawartha Conservation (2010) conducted a water quality assessment in Lake Scugog and found that natural sources and atmospheric deposition account for approximately 40.4% of the TP loading in Lake Scugog, while the largest human-caused source of phosphorus is agricultural run-off, which makes up about 23.5%. Despite taking up only 3.5% in total area of the watershed, urban run-off – mostly from manicured green spaces like golf courses, sports fields and parks – still contributes roughly 18.2% of TP. Septic systems are also estimated to contribute about 9.7% of TP, followed by rural road run-off (6.4%) and the Port Perry Sewage Treatment

Plan (1.8%). The report also suggested that the TP load into Lake Scugog must reduce from the current 9,400 kg to approximately 6,000 to 6,200 kg per year in order to improve water quality and maintain the lake's ecosystem. However, this is likely an underestimate of the effort needed to reduce eutrophication in Lake Scugog, as it does not take into account sources of P from internal loading due to an increasingly anoxic sediment-water interface (Harrow-Lyle and Kirkwood 2020a). Despite lake management efforts to reduce TP loading into the lake (e.g. limiting the use of fertilizers, upgrading septic systems and stormwater management infrastructure), TP concentrations were found to be consistently over the 30 µg/L threshold during the Ontario Tech University monitoring program, indicating eutrophic (and at times hypereutrophic) conditions (Harrow-Lyle & Kirkwood, 2020a). Nearshore TP concentrations were highest in areas with developed shorelines at 37.56 µg/L, comparing to 25.96 µg/L in agricultural zones and 25.63 µg/L in natural areas (Smith & Kirkwood, 2020).

Efforts to control nutrient concentrations into Lake Scugog will further be complicated by climate change. Climate warming is considered one of the major factors that play an interactive role in modulating algal bloom frequency, intensity, geographic distribution and duration (Molot et al., 2021; Paerl et al., 2011). Warmer water encourages the growth of potentially harmful cyanobacteria such as *Microcystis* over other non-harmful algae, as cyanobacteria grows better at higher temperature (often over 25°C) (Paerl & Huisman, 2008; Smith & Kirkwood, 2020). Warmer water also increases thermal stratification, which lengthen growth periods and favours the growth of cyanobacteria and dinoflagellates. During stratified periods, these phytoplankton taxa have the ability to control their buoyancy, allowing them to suppress their opponents that are unable to migrate through competition for light and surface nutrient (Paerl & Huisman, 2008; United States Environmental Protection Agency, 2013). Increased thermal stratification also

increases risk of anoxia at the sediment-water interface, which can result in internal loading of iron and phosphorus to promote blooms (Molot et al. 2021).

Changes in hydrological regimes can also have major effects on phytoplankton blooms. When precipitation increases, water discharge may prevent blooms by flushing, but may also increase nutrient run-off into waterbodies and thus facilitate blooms (Paerl & Huisman, 2008). In shallow lakes like Lake Scugog, thermal stratification can form and disappear on a daily basis (Condie & Webster, 2001), and elevated water levels might increase the risk of prolonged thermal stratification. Climate change-induced droughts also increase salinity of water, which can cause salt stress leading to leakage of cells and the release of toxins (Paerl & Huisman, 2008; United States Environmental Protection Agency, 2013). This increase in salinity is exacerbated by the increased loading of chloride (Cl) to urban waterbodies from road salt application (Dugan et al., 2017). High Cl concentrations are toxic to freshwater organism, and increased levels of Cl in Lake Scugog might shift communities to more tolerant taxa like *Microcystis* (Harrow-Lyle & Kirkwood, 2020a).

3.3.2 Decline of Local Fisheries

Lake Scugog falls under the Ontario Ministry of Northern Development, Mines, Natural Resources and Forestry fisheries management zone 17, which is the heaviest-fished region in the entire province of Ontario (Robbins, 2019). Walleye (*Sander vitreus*) was introduced to Lake Scugog from the 1920s through the 1940s, following the introduction of largemouth bass (*Micropterus salmoides*) in the early 1900s (Kawartha Conservation, 2010). Bluegill (*Lepomis macrochirus*) was introduced in the 1970s, followed by black crappie (*Pomoxis nigromaculatus*) in the 1990s. These introduced species, together with native species like muskellunge (*Esox masquinongy*) and smallmouth bass (*Micropterus dolomieu*), make up the present-day sport fish

community (Kawartha Conservation, 2010). Walleye is the primary targeted species in the lake, however the species abundance has declined significantly since the 1980s, to the point that the then-Ministry of Natural Resources and Forestry had to place a year-round closure on walleye fishing starting on January 1st, 2016 to protect the population (Kawartha Conservation, 2010; Ontario Federation of Anglers and Hunters, n.d.). On average, recreational anglers spend over 200,000 fishing hours on Lake Scugog annually, generating $10 to $15 million each year (Hall, 2020). The livelihood of many business and tourist establishments on Lake Scugog rely on healthy fisheries, which has historically depended on a healthy walleye population (Ministry of Natural Resources and Forestry, 2015).

Water level has a big impact on local recreational fisheries as it changes the living and breeding conditions of fish. Walleye is a cool-water species that prefers low temperature (18–22°C) and low light conditions (Chu et al., 2004). Therefore, low water levels – especially seasonal water drawdowns during the spawning period – will have negative effects on walleye population. On the other hand, these conditions have made fish habitats more suitable for other species. Bass (*Micropterus* spp.) species which are very well adapted to hunting in high light conditions (Robillard & Fox, 2006) and muskellunge, whose eggs rely on low water level to be aerated (Dombeck et al., 1984) are warm-water fish that benefit from decreasing water levels, seeing an increase in relative abundance during drier periods (Kawartha Conservation, 2010).

Local fish community also depends on the food web within Lake Scugog. Climate change affects all trophic levels, including phytoplankton, zooplankton and macroinvertebrates, subsequently affecting fish community (Jeppesen et al., 2014). Fish communities are also strongly affected by eutrophication. In recent years, the blooms of *Mycrocystis* – an opportunistic cyanobacteria – have had negative impacts on macrophytes, macroinvertebrates and fish by

blocking light for photosynthesis and causing anoxic conditions at the sediment-water interface (Harrow-Lyle & Kirkwood, 2020a). The resulting impacts on the fish communities has not been addressed.

3.3.3 Other Management Problems

Lake Scugog is a tourist and cottage destination, and water level directly affects what recreational activities may be available on the lake such as boating and fishing, as well as market values of lakeshore properties. Water level regulation has been a continuous issue between residents and the Trent-Severn Waterway. Currently, the Lake Scugog Enhancement Project – an environmental improvement and dredging project planned for the Port Perry Bay – is expected to begin in fall 2021. The project aims to use dredged material to create a four-acre wetland in the southwest corner of the lake at the mouth of Cawkers Creek – the most urbanized stream among all major watercourses of the watershed (Kawartha Conservation, 2010). The artificial wetland will naturally filter out sediment and run-off, thus reduce excess nutrients and increase biodiversity. It will also increase the water depth at the Port Perry marina, improving boating activities (Hall, 2021).

As Lake Scugog is a part of the major Trent-Severn Waterway, its water level and quality affect not only locals, but also downstream users. Lake Scugog is the second largest (16%) source of water for Sturgeon Lake – one of the top end lakes in the Kawartha Lakes chain, which collectively form the central part of the waterway. As Sturgeon Lake, as well as the Kawartha Lakes in general, are under multiple stressors such as eutrophication, invasive species and climate change (Kawartha Conservation, 2014), water quality management of Lake Scugog plays in important role in maintaining the ecological health of the entire system. Moreover, Lake Scugog water level management is directly influenced by the waterway's water levels – which

are managed by Parks Canada based on numerous factors such as hydropower generation, wildlife protection, flood mitigation, navigation and recreational activities (Parks Canada, n.d.)

In recent years, Lake Scugog has shown signs that it is in the midst of a transformation from a macrophyte-dominated lake (Figure 3.2) to an algal-dominated lake, linked to the recent invasion of the lake by the macroalga species starry stonewort (*Nitellopsis obtuse*) (Harrow-Lyle & Kirkwood, 2020a). Starry stonewort has significantly reduced macrophyte community richness and may be a significant biotic driver of *Microcystis* blooms in Lake Scugog, which might have considerable impacts on local fisheries (Harrow-Lyle & Kirkwood, 2020b). Other invasive species include zebra mussel (*Dreissena polymorpha*), rusty crayfish (*Orconectes rusticus*) and purple loosestrife (*Lythrum salicaria*) (Kawartha Conservation, 2010). Zebra mussels are found mainly associated with starry stonewort, which provide a firm substrate for zebra mussel attachment in an otherwise mainly soft-substrate system; the facilitation of zebra mussel invasion may be the primary mechanism through which starry stonewort promotes *Microcystis* blooms (Harrow-Lyle & Kirkwood, 2020b). The cumulative effects of the interaction between climate change and invasive species, especially starry stonewort, on water quality and fish habitat are still uncertain (Larkin et al., 2018).

Figure 3.2. Macrophytes (milfoil – *Myriophyllum*) dominate Lake Scugog.

CHAPTER FOUR: METHODS

4.1 Field Methods

Gravity cores (~60-70 cm in length) were collected from both the east basin and west basin to reconstruct ecological changes in Lake Scugog over the past ~150 years (Figure 4.1). Gravity cores are capable of capturing recently deposited sediments with high water content, which makes this an ideal coring method for studying recent (i.e. post-industrial) changes (Blomqvist, 1991; Glew et al., 2001). In June 2016, researchers from the University of Waterloo used a Uwitec^{TM} gravity core to collect a 66-cm sediment core from the central area of Port Perry Bay in the west basin (Lat 44.107388° Long -78.936734°) as part of a contract with Kawartha Conservation to reconstruct sedimentation rates in Port Perry Bay to support planning for the Lake Scugog Enhancement Project (Wiklund & Hall, 2017). In July 2018, I collected a 71-cm gravity core from the deepest part of the east basin (Lat 44.20222° Long -78.79411°) with a UwitecTM gravity core (Figure 4.2a). Both cores were sectioned same-day using a modified Glew extruder (Glew et al., 2001; Wiklund & Hall, 2017). The east basin core was sectioned into 0.5 cm intervals and the west basin core was sectioned into 1.0 cm intervals.

In February 2020, I collected a 2.5-meter-long sediment core from Port Perry Bay using an Icelandic Piston Corer (Fisher et al. 1992) from the same location where the gravity core was taken (Lat 44.107388° Long -78.936734°) to reconstruct the Holocene environmental history of the site (Figure 4.2b). Piston cores are useful for capturing long (> 1 m) sediment records, but do not adequately capture the most recent post-1850 sediments (Blomqvist, 1991). The core was kept frozen, then later measured and sectioned into 1 cm intervals in the lab in July 2020 under clean, sterile conditions.

4.2 Sediment Chronologies

The west basin gravity core was dated at the University of Waterloo using ^{210}Pb by gamma-ray spectrometry (Wiklund & Hall, 2017). The east basin core was ^{210}Pb-dated at Chronos Scientific Inc. (Ottawa, Ontario) using alpha-ray spectrometry. The gamma spectrometry is non-destructive to sediment samples, providing direct ^{210}Pb measurements as well as other radioisotopes such as ^{137}Cs, which was produced during atmospheric bomb testing (Jaakkola et al., 1983). In contrast, the alpha spectrometry is destructive and provides indirect ^{210}Pb information through the measurements of ^{210}Po (the product of ^{210}Pb decay), with the assumption of isotopic equilibrium between ^{210}Po and ^{210}Pb (Appleby et al., 1986; Zaborska et al., 2007). Both cores were dated using the Constant Rate of Supply (CRS) model – the most widely used model in which the supply of ^{210}Pb is assumed to be constant, while the sedimentation rate is varied (Appleby, 2001). For the west basin core, loss-on-ignition data available from Wiklund and Hall (2017) was also used as a supplementary dating record to identify the timing of the construction of the Lindsay Dam. Loss-on-ignition provides estimations of organic, carbonate and water content in sediments (Heiri et al., 2001), and an upsurge in sediment organic matter originating from submerged material following the formation of a reservoir is expected.

The piston core was dated using radiocarbon dating. Three terrestrial plant macrofossils such as visible plant fibers or wood fragments were extracted from different depths (~143 cm, ~211 cm and ~254 cm) in the core and sent to the Lalonde lab at the University of Ottawa for ^{14}C dating. Radiocarbon analyses are conducted using a 3MV tandem accelerator mass spectrometer, with $^{12,13,14}C^{+3}$ ions measured at 2.5 MV terminal voltage. The fraction modern carbon $F^{14}C$ (the ratio of the sample $^{14}C/^{12}C$ ratio to the standard $^{14}C/^{12}C$ ratio) was corrected, and then used to

calculate radiocarbon ages using the formula -8033ln($F^{14}C$), reported in ^{14}C yr BP (BP=AD 1950) (Stuiver & Polach, 1977).

4.3 Subfossil Diatom Analysis

For diatom analysis, approximately 0.5 grams of wet sediment from each interval was placed into glass scintillation vials, and then organic matter was digested following the hydrogen peroxide (H_2O_2) method outlined by Battarbee et al. (2001). To remove carbonate content as well as many other metal salts and oxides, each vial was treated with 10% hydrochloric acid (HCl) over 24 hours and rinsed with deionized water over several days until neutral. The vials were then filled with 30% H_2O_2 and partially submerged in a water bath at approximately 70°C for a few hours to remove organic matter, and then rinsed again with deionized water over the course of seven days to dilute the H_2O_2. Small portions of the final slurries were then put onto coverslips in four different dilutions and dried at room temperature inside a covered slide box to avoid contamination. After that, the coverslips were mounted onto microscopes slides using Naphrax®. The slides were viewed under an oil immersion lens (1000x magnification) of a Leica compound microscope, equipped with a digital camera and imaging software to capture specimen images. A minimum number of 400 valves outlined by Rühland & Smol (2005) were counted for each slide. Diatom identification was based on the guidelines in Süßwasserflora von Mitteleuropa by Krammer and Lange-Bertalot (1986–1991), as well as supplemental information from the website Diatoms of North America (https://diatoms.org/).

Hill's N2 diversity index for each slide was calculated on the entire raw data set, using the rioja and vegan packages in R Studio program. Relative abundance of each species was calculated in Microsoft Excel, and species that had similar ecology and showed similar trends in population were combined while the least abundant species (< 2% abundance) were removed

from further analysis. Then a stratigraphy of relative abundance was produced also using R Studio. A constrained incremental sum of squares (CONISS) – a multivariate method for quantitative definition of stratigraphic zones where only stratigraphically adjacent clusters were considered for merging – was performed on the entire data set to identify stratigraphic zones of similar diatom assemblages and establish times of significant assemblage changes (Grimm, 1987). Furthermore, the broken-stick model – a zonation analysis method that uses changes in total variance comparing to the modelled proportion to allocate samples into zones – was used to identify the number of significant zones (Bennett, 1996).

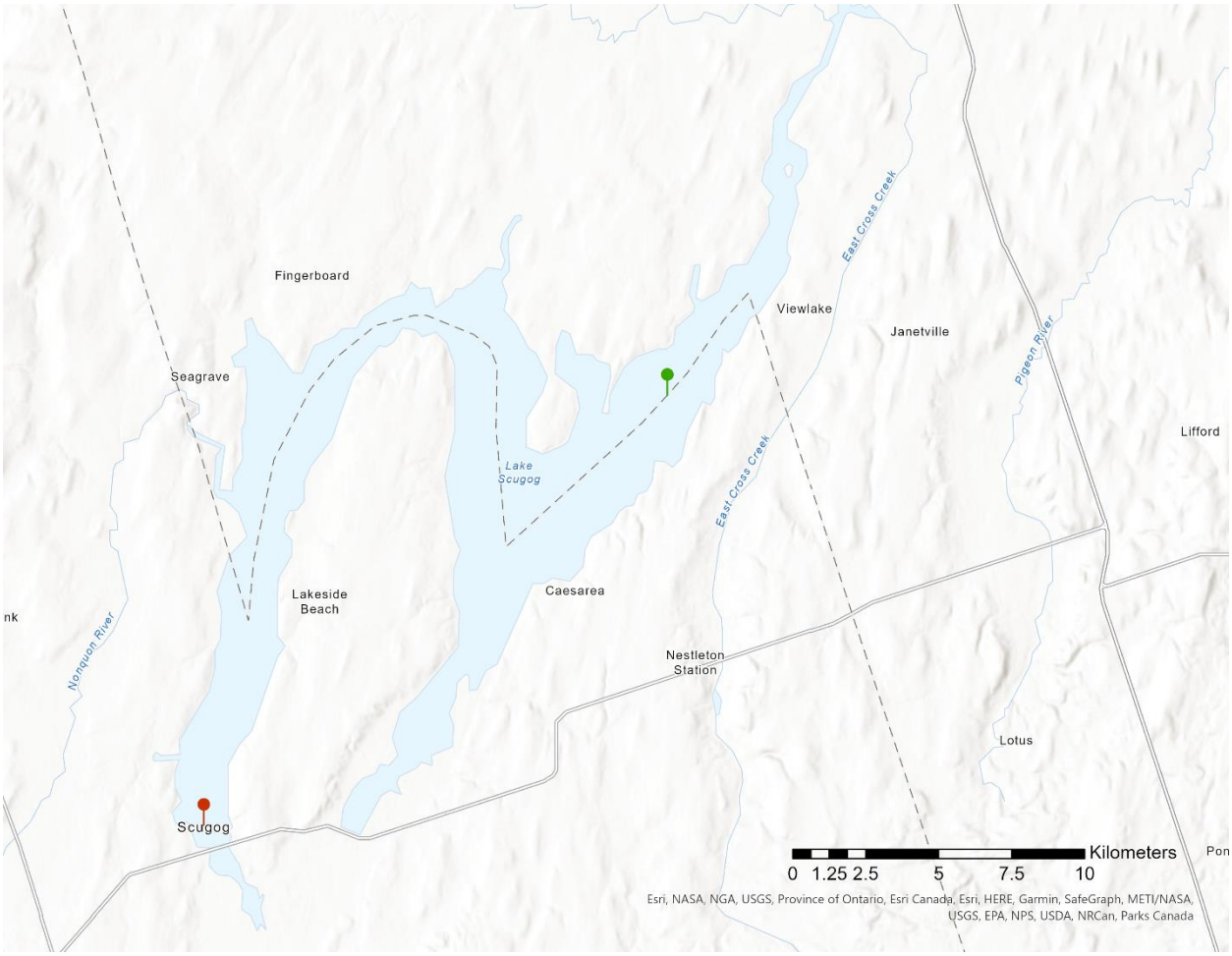

Figure 4.1. Coring locations of the gravity cores (west basin – red and east basin – green) and piston core (west basin).

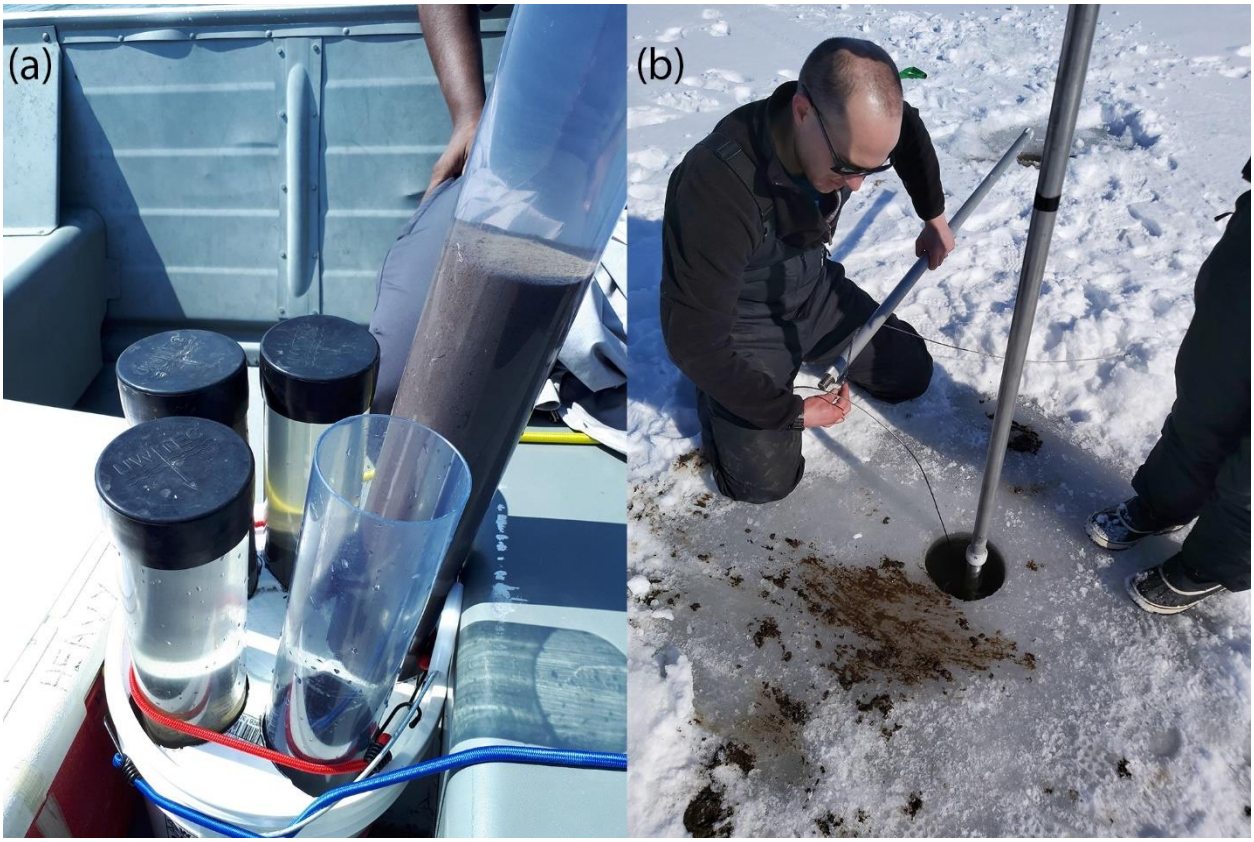

Figure 4.2. Collecting the east basin gravity core (a) and west basin piston core (b).

CHAPTER FIVE: RESULTS

5.1 Gravity Cores (Recent Paleoenvironmental Changes)

5.1.1 East Basin

The CRS ^{210}Pb age model results showed a generally exponential decrease in ^{210}Pb measurements with depth (Figure 5.1). However, there was some irregularities from a clean exponential decline, suggesting an inconsistency in the sedimentation rate over the last ~150 years, which is typical and expected. The earliest date returned by the CRS model was ~1880 at 50 cm core depth.

The CONISS analysis and broken-stick model identified three significant groups of diatom assemblages (Figure 5.2). In Zone 3 prior to ~1930 (below 30 cm core depth), the diatom composition was dominated by the tychoplanktonic *Aulacoisera ambigua*, with relative abundance ranging from 55.1% to 71.4%. Small, benthic *Fragilaria* was the second most abundant group, accounting for 15.2-33.6% of the assemblages. Zone 2, from ~1930 to ~1950 (25 – 20 cm depth), represents a period of rapid transition in diatom assemblages. *A. ambigua* quickly declined while small, benthic *Fragilaria* rapidly increased to become the most dominant species from the early 1950s until now, ranging from 54.7% minimum to 75.9% maximum relative abundance. In Zone 1 (~1950 – present; 18 – 1 cm depth), other benthic taxa also increased in relative abundance, especially *Achnanthes* spp. and *Navicula* spp while planktonic *Fragilaria* and other planktonic taxa such as *Cyclotella bodanica* and *Cyclotella distinguenda* remained somewhat consistent throughout the transition. *Cyclotella ocellata* in particular significantly increased in popularity starting from the late 1980s - early 1990s, becoming the dominant planktonic diatom taxon.

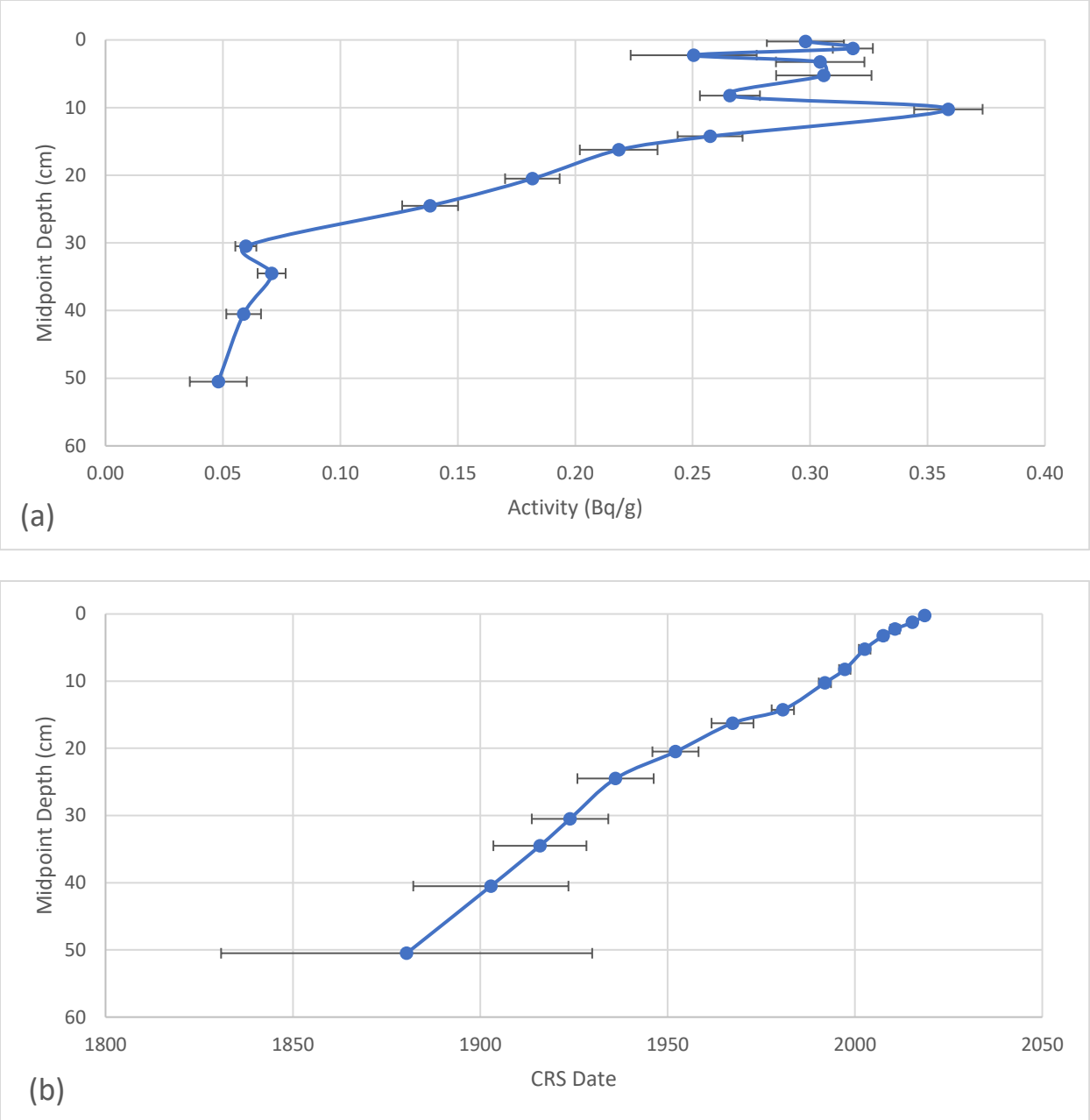

Figure 5.1. (a) Sediment core depth vs. ^{210}Pb activity, and (b) Sediment core depth vs. ^{210}Pb-inferred date in the east basin gravity core using the CRS model.

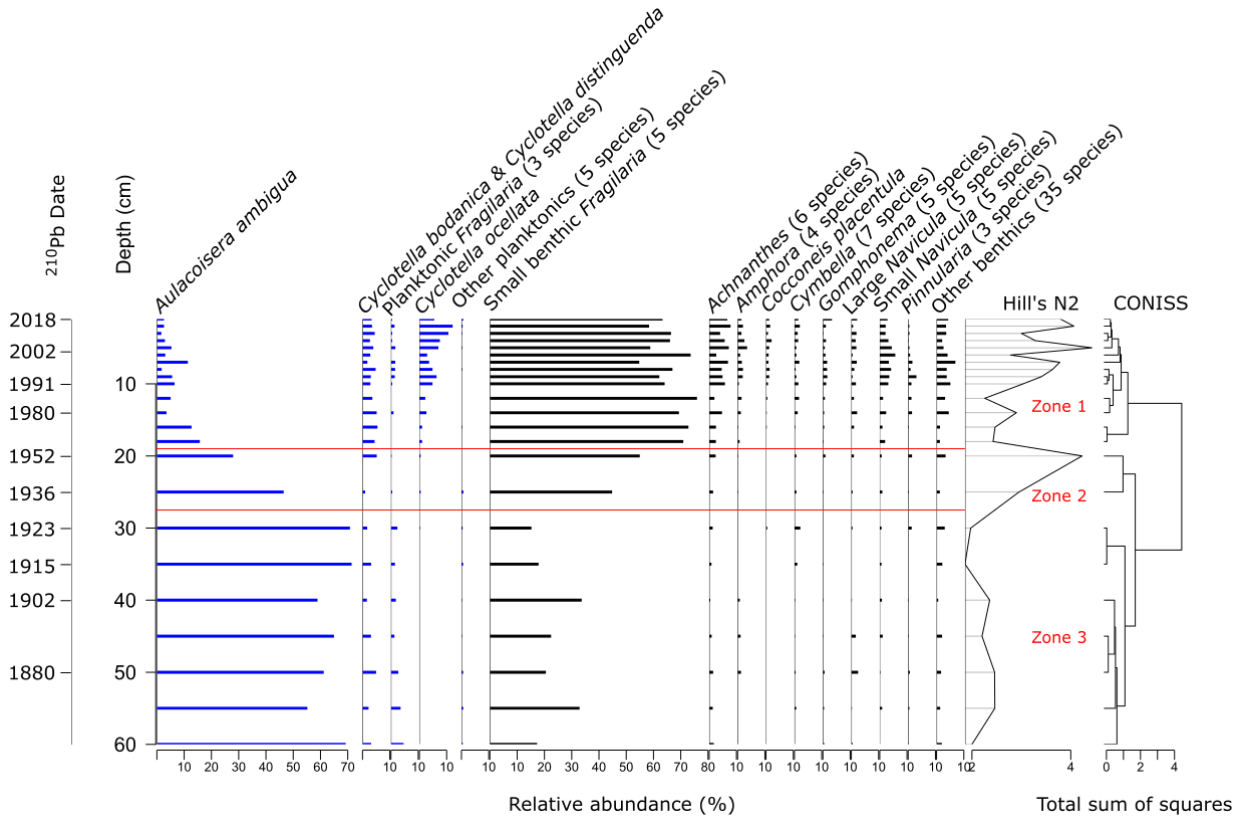

Figure 5.2. A stratigraphic diagram of diatom assemblages in a gravity sediment core collected from the east basin of Lake Scugog (southern Ontario, Canada). Sediment core depth and ^{210}Pb-inferred date using the CRS model are shown on the left. The results of the Constrained Incremental Sum of Squares (CONISS) cluster analysis are shown on the right. Red lines represent CONISS zones determined to be significant based on the broken-stick model.

5.1.2 West Basin

The CRS ^{210}Pb age model results of the west basin gravity core showed some departure from an otherwise exponential decline in ^{210}Pb activities with depth, suggesting that the sedimentation rate has not been constant over the last ~150 years (Figure 5.3). The earliest date returned by the CRS model was ~1858 at 39 cm core depth. Linear extrapolation of CRS dates below the ^{210}Pb dating horizon started from ~1852 at 40 cm to ~1657 at 52 cm, giving an

estimated age of ~360 years for the entire sediment core (Wiklund & Hall, 2017). This would place the timing of the construction of the Lindsay Dam at a core depth of ~41 cm; however, sedimentation rate changes following reservoir creation and thus linear extrapolation of CRS dates may not be appropriate for determining timing of dam construction. The extrapolated dates were compared against loss-on-ignition data from Wiklund and Hall (2017), which showed a transition in sediment composition at 44 cm that is consistent with what is expected following reservoir creation, going from high carbonate content and low organic content to low carbonate content and very high organic content, as well as an increase in water content (Figure 5.4). From this, I place the approximate timing of the formation of present-day Lake Scugog at 44 cm.

Three significant groups of diatom assemblages in the gravity core from the west basin of Lake Scugog were identified by the CONISS analysis and broken-stick model (Figure 5.5). In Zone 3 (60 – 55 cm core depth), the diatom community had high abundances of *Mastogloia smithii* and *Neidium* spp. (composed of *Neidium ampliatum* and *Neidium iridis*). At Zone 2 (50 cm), the diatom assemblages saw a transition to a community predominantly made up of small, benthic *Fragilaria*. In Zone 1 (45 – 1 cm depth; assumed to be post-1844 based on the loss-on-ignition results), the diatom composition remained fairly consistent, with small, benthic *Fragilaria* accounting for 74.1-89.9% of the assemblages.

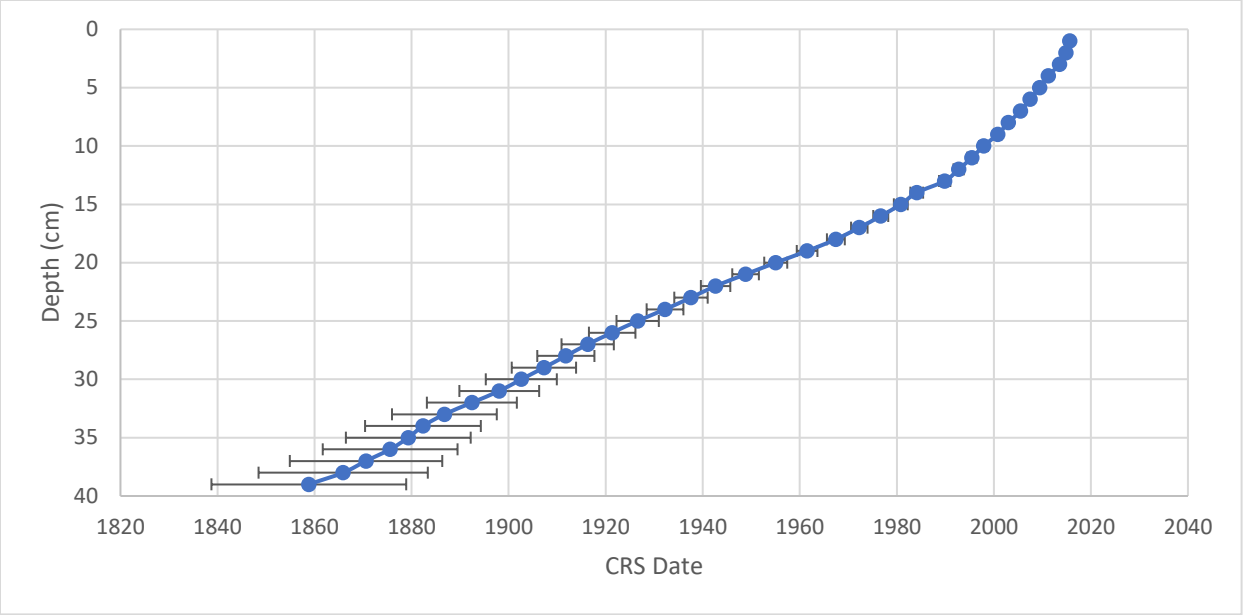

Figure 5.3. Sediment core depth vs. ^{210}Pb-inferred date in the west basin gravity core using the CRS model [figure recreated from data in Wiklund & Hall (2017)].

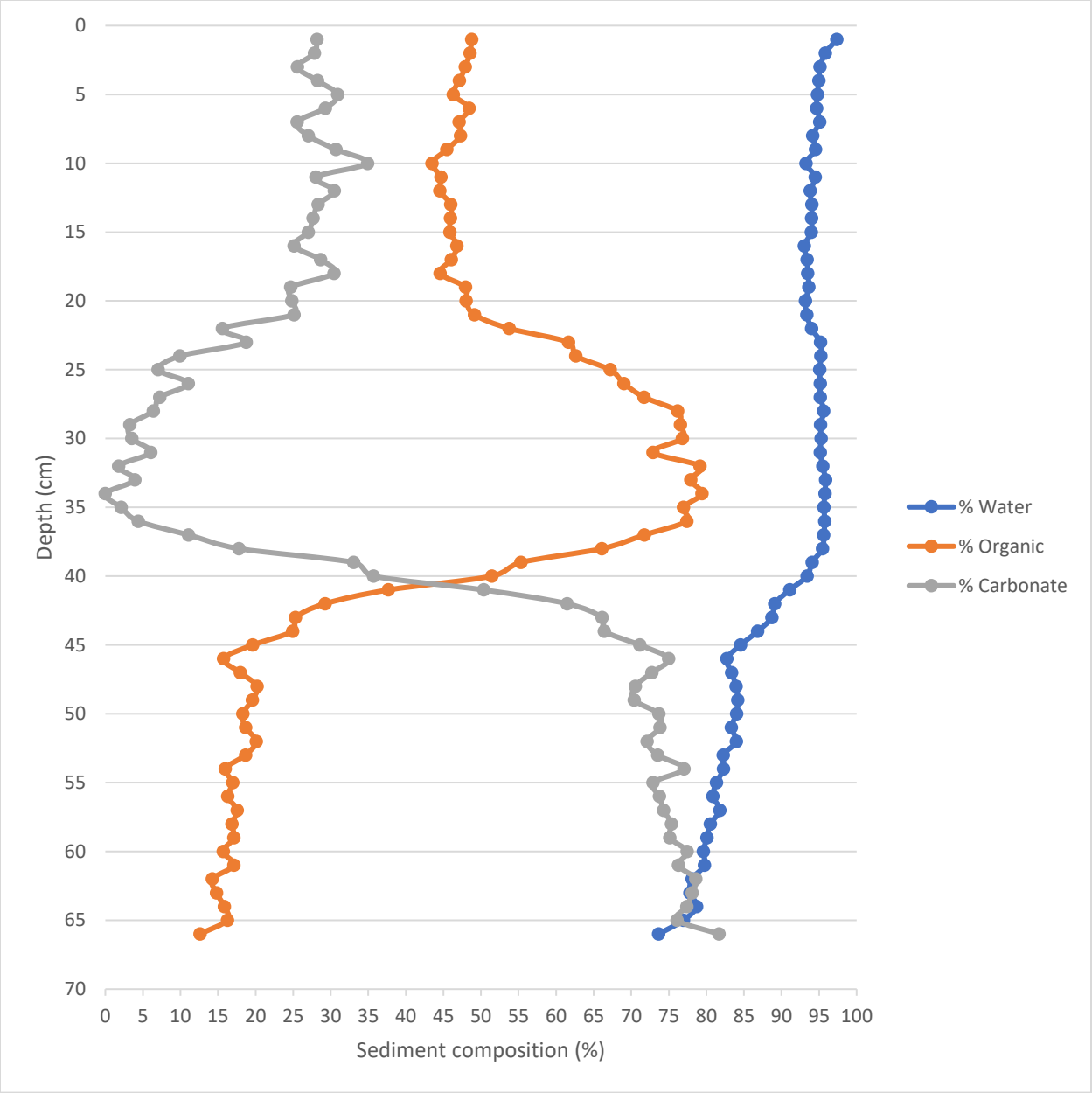

Figure 5.4. Loss-on-ignition data from the west basin gravity core showing changes in the water, organic matter and carbonate content of the sediments [figure recreated from data in Wiklund & Hall (2017)].

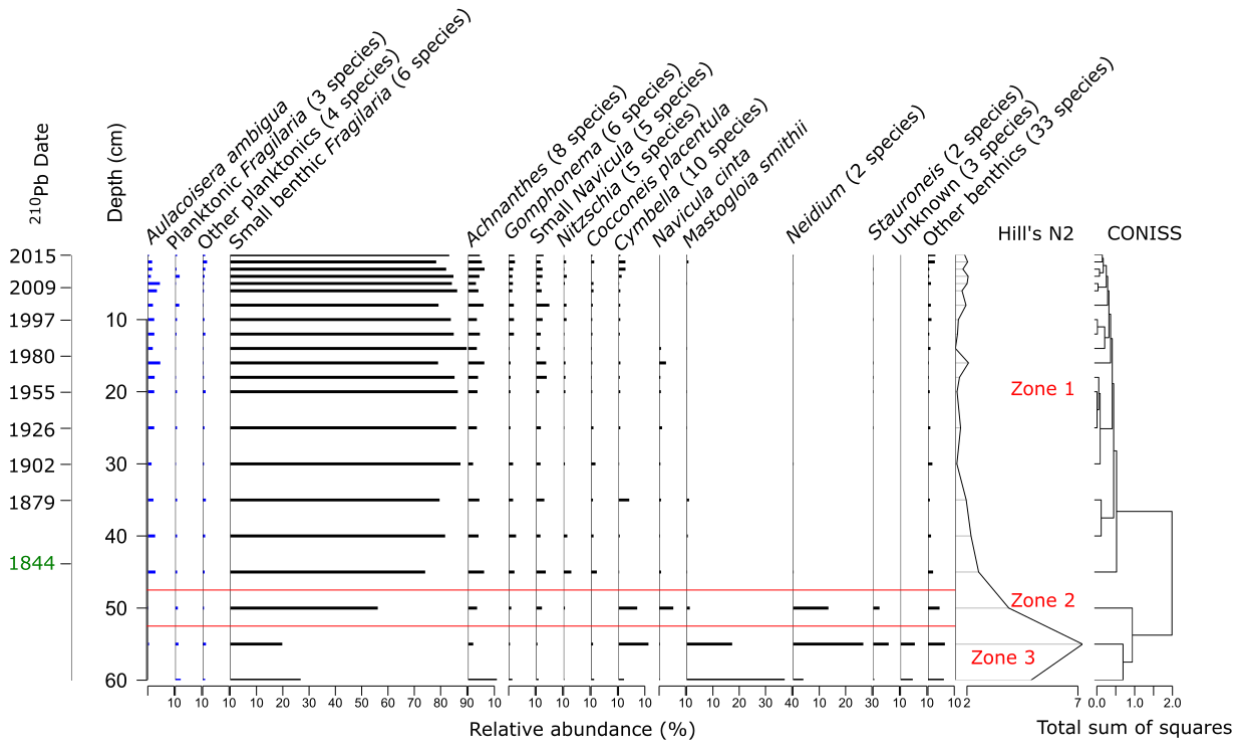

Figure 5.5. A stratigraphic diagram of diatom assemblages in a gravity sediment core collected from the west basin of Lake Scugog (southern Ontario, Canada). Sediment core depth and ^{210}Pb-inferred date using the CRS model are shown on the left. The 1844 date based on the loss-on-ignition data is marked in green. The results of the Constrained Incremental Sum of Squares (CONISS) cluster analysis are shown on the right. Red lines represent CONISS zones determined to be significant based on the broken-stick model.

5.2 Piston Core (Holocene Paleoenvironmental History)

Only three terrestrial plant samples were recovered in the core that could be used for ^{14}C dating (at ~143 cm, ~211 cm and ~254 cm core depth). The core was estimated to be ~7600 BP at ~254 cm, ~6600 BP at ~211cm and ~5300 BP at ~143 cm (Table 5.1). I also approximated the core depths for ~4000 BP (~95 cm depth) and ~3000 BP (~40 cm depth) using linear interpolation assuming a constant sedimentation rate.

The CONISS analysis and broken-stick model identified six significant groups of diatom assemblages in the piston core from the west basin of Lake Scugog (Figure 5.6). Zone 6 (270 – 185 cm depth) marked the early post-glacial history of the west basin from ~7600 to ~6000, which was characterized by the dominance of *Mastogloia smithii*, accounting for 60% to 95% of the assemblages. *Neidium* spp. and *Navicula diluviana* are other two significant groups in this zone with much smaller abundances, accounting for 0.7-19.7% and 0.2-11% respectively.

In Zone 5 (180 – 145 cm; ~6000 BP to ~5300 BP), *M. smithii* and *Neidium* spp. showed a generally opposite fluctuation trend: as one increased, the other decreased. *M. smithii* also slightly decreased in abundance comparing to Zone 6, ranging from 25.4% to 81.5%.

Zone 4 (140 – 110 cm; ~5300 BP to ~4100 BP) saw a dominance of *Neidium* spp. in 140 – 130 cm core depth, accounting for 71.7-97.8% of the assemblages. The taxon dropped to 15.8% at 125 cm, but gradually increased up to 39.4% at 110 cm depth. *M. smithii* kept declining in abundance comparing to previous zones, and only reached the maximum percentage of 50.9%. *M. smithii* and *Neidium* spp. also continued to show the opposite fluctuations previously observed in Zone 5.

Zone 3 (105 – 90 cm; ~4100 BP to ~3800 BP) was characterized by the dominance of *Neidium* spp. (80.4-92.6%). However, the taxa dropped in numbers in Zone 2 (85 – 70 cm; ~3800 BP to ~3500 BP), accounting for only 6.2-10.1% of the assemblages. *M. smithii* (22-35.9%) once again became the most abundant taxon in Zone 2. Some other species such as *Pinnularia viridis* and *Gomphonema pumilum* also increased in numbers in this zone.

In Zone 1 (65 – 5 cm; ~3500 BP to ~2000 BP), *Cymbella ehrenbergii* increased in relative abundance (12-34%), and together with *Neidium* spp. (22.5-60.7%) made up the majority of the diatom assemblages post ~3500 BP. Maximum relative abundance of *Neidium* spp. in this zone was 60.7% at ~3000 BP, and the taxa generally declined in numbers overtime. *M. smithii* became almost absent in this zone, however, several other taxa such as Amphora spp. (*Amphora libyca* and *Amphora ovalis*) and *Stauroneis phoenicenteron* also increased in relative abundances.

Table 5.1. ^{14}C results of the west basin piston core.

Depth (cm)	**Material**	**^{14}C yr BP**
143	Terrestrial plant remains (non-woody)	5296
211	Wood	6582
254	Wood	7599

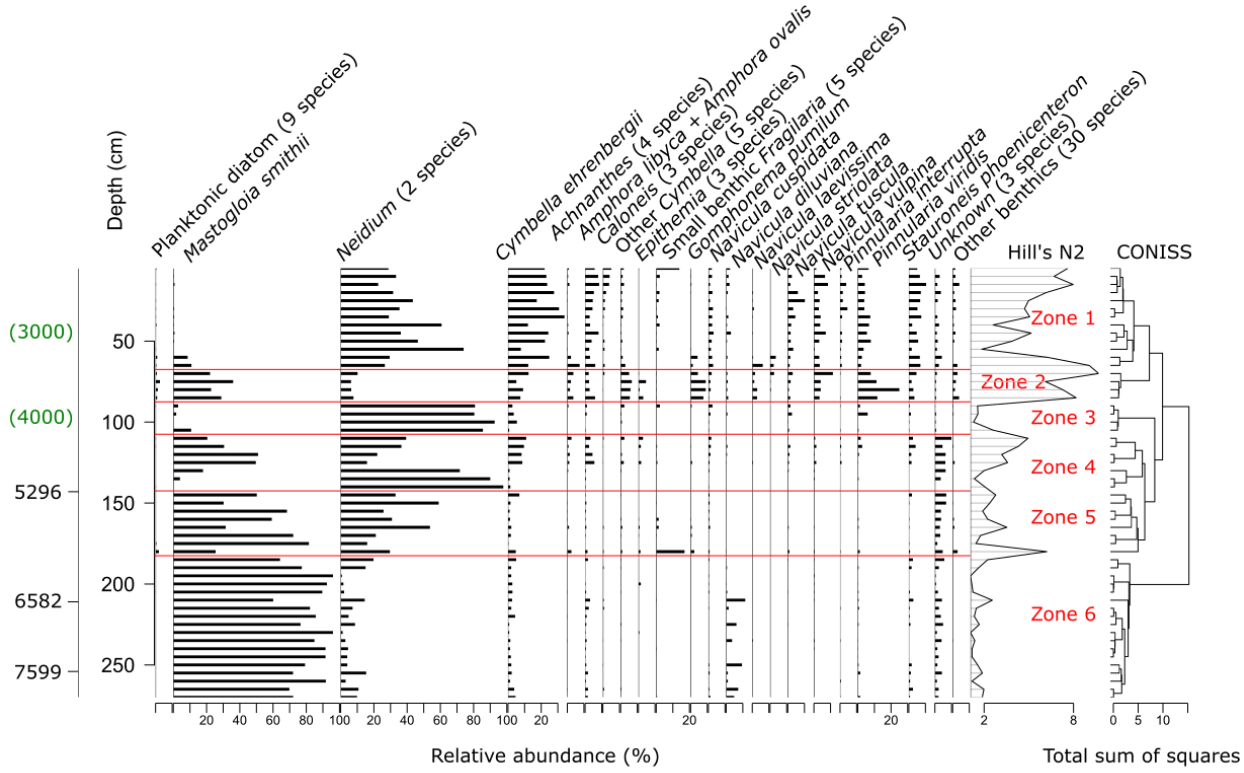

Figure 5.6. A stratigraphic diagram of diatom assemblages in a piston sediment core collected from the west basin of Lake Scugog (southern Ontario, Canada). Sediment core depth and ^{210}Pb-inferred date using the CRS model are shown on the left. The results of the Constrained Incremental Sum of Squares (CONISS) cluster analysis are shown on the right. Red lines represent CONISS zones determined to be significant based on the broken-stick model.

CHAPTER SIX: DISCUSSION

6.1 Diatoms in the East Basin Might Be an Indication of Recent Climate Warming

The diatom assemblages from the gravity core of the east basin showed a classic response indicating a transition from a well-mixed to a stratified (or periodically stratified) lake, driven by recent climate warming: heavier tychoplanktonic (i.e. dependent on turbulence to remain suspended in the water column) diatoms are replaced by more buoyant species that are more competitive in thermally stable conditions. This diatom assemblage shift has been documented extensively across the Northern Hemisphere and has been inferred to be a response to a longer ice-free period and increased thermal stability (Rühland et al., 2015).

In Lake Scugog, *Aulacoisera ambigua* was the dominant tychoplanktonic diatom prior to the 1930s. Like other members in the genius, the species has been described as a large-celled, tubular-shaped tychoplankton species. Two forms of the taxon were identified in the core: medium-sized shell with relatively coarse areolae and narrow, thin-walled shell with fine areolae (Stone et al., 2011) (Figure 6.1). *Aulacoisera* taxa are heavy and fast-sinking, and thus require stronger vertical mixing of the water column to stay in the photic zone (Rühland et al., 2015). From the 1930s to the early 1950s, the population of *A. amgibua* decreased from nearly 50% to less than 20% relative abundance, signaling a reduction of water column mixing, likely due to increases in lake surface water temperatures. This finding is consistent with the observations from the 4-year limnological monitoring program conducted monthly by researchers of Ontario Tech University during the ice-free season from 2016-2019, in which periodic thermal stratification was documented in the eastern arm of the lake (Harrow-Lyle & Kirkwood, 2020a). The changes in diatom assemblages suggests that the observations made by Ontario Tech

University are evidence of climate warming impacts and not just a typical state of the lake that has persisted since its formation.

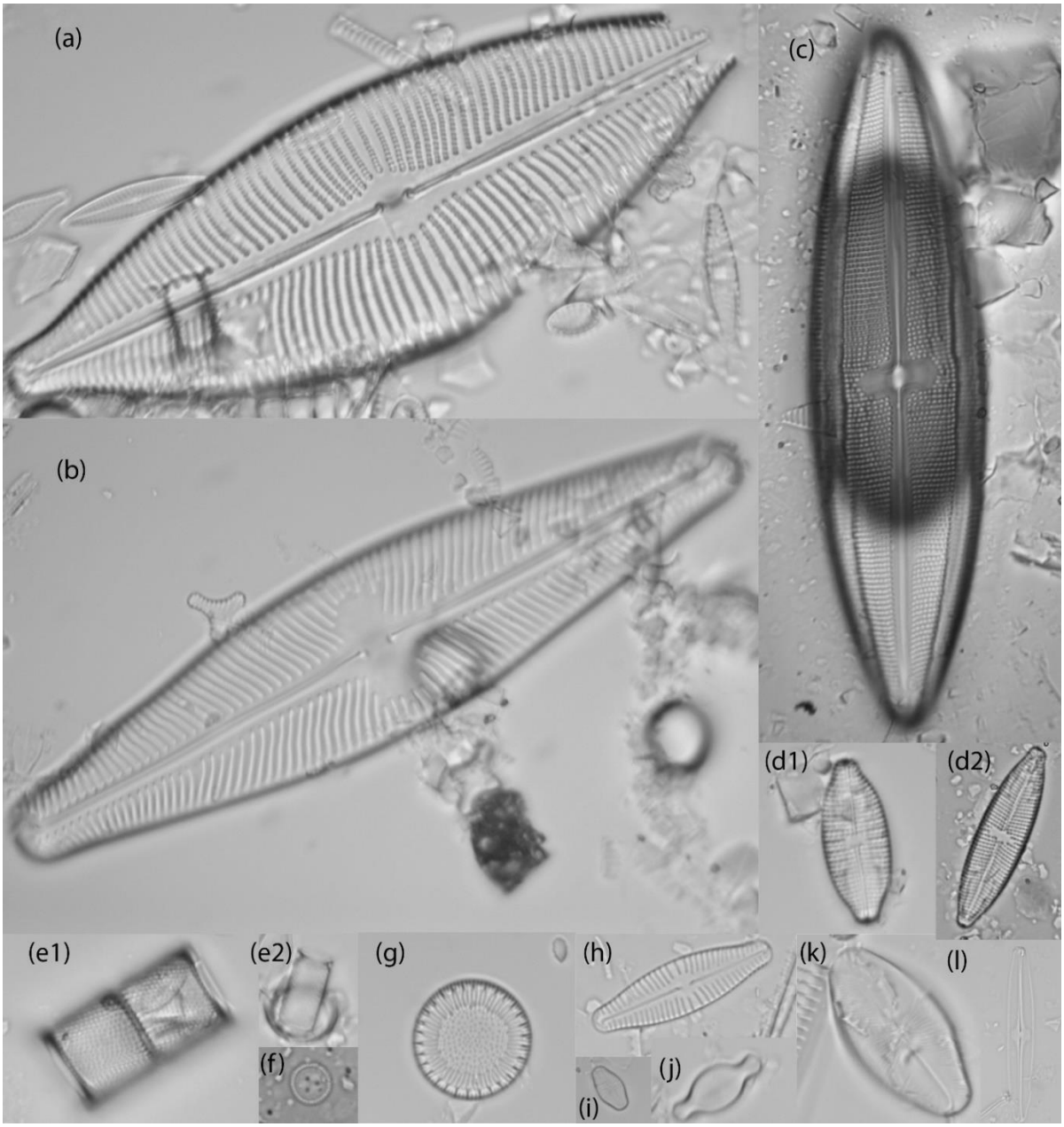

Figure 6.1. Examples of diverse diatom species found in Lake Scugog: (a) *Cymbella ehrenbergii*, (b) *Navicula aurora*, (c) *Neidium iridis*, (d) *Mastogloia smithii*, (e) *Aulacoisera ambigua*, (f) *Cyclotella ocellata*, (g) *Cyclotella bodanica*, (h) *Navicula diluviana*, (i) *Navicula vitabunda*, (j) *Navicula schadei*, (k) *Achnanthes flexella*, (l) *Caloneis molaris*.

Since the 1950s, *Cyclotella* taxa increased to become the dominant planktonic diatoms in the east basin of Lake Scugog, likely due to their small-celled, pancake-shaped, more buoyant lifeform. During more thermally stable periods, small centric cyclotelloid diatoms have a competitive advantage because they have a reduced sinking velocity, thus allowing them to stay in the photic zone longer and better compete for light and nutrient resources (Rühland et al., 2015). Previous studies found that small *Cyclotella* species were more common in relatively pristine, oligotrophic lakes, and more likely absent from lakes that were directly impacted by anthropogenic factors such as eutrophication, pollution and overdevelopment of shorelines (reviewed in Rühland et al., 2008). This could explain why the taxa (*Cyclotella bodanica*, *Cyclotella distinguenda*, *Cyclotella ocellata*) only reached maximum relative abundances of ~16% in Lake Scugog. *C. ocellata*, however, clearly increased in the past ~20 years, and it is a cyclotelloid species that is known to prefer somewhat higher nutrient contents (Van Dam et al., 1994).

The transition signal from *Aulacoisera* to *Cyclotella* is consistent with hemispheric trend in diatom assemblage response to climate warming and suggests that the Lake Scugog region has experienced climate warming since at least the 1950s. The timing of the transition in the east basin ca. 1950 is similar to the timing of diatom community shift in the nearby Lake Simcoe (southern Ontario) (Hawryshyn et al., 2012), but much earlier than Eagle Lake (located near Kingston, Ontario, northeast of the Kawartha Lakes) which experienced this shift in diatom assemblages in the early 1980s (Nelligan et al., 2016). Similarly, Lake Ontario paleolimnological studies documented this change in the early 2000s (Reavie et al., 2017). This highlights the regional variations in climate warming, as well as the impacts of lake morphology in responding to a changing climate. Because Lake Simcoe and Lake Scugog are located near each other, and

both are parts of the Trent-Severn Waterway, the similar timing of diatom shifts may indicate a shared trajectory of warming air temperatures. In contrast, Eagle Lake is located much further northeast, thus may have experienced warming air temperatures and subsequent surface water temperatures and diatom transitions later. While Lake Ontario is located more southerly, it is a very large body of water. Lakes with significantly greater water volumes and depths experience a substantial lag in heating and cooling (Hondzo & Stefan, 1993), therefore it is not a surprise that the diatom assemblages in Lake Ontario transitioned decades later after Lake Scugog.

Small, benthic *Fragilaria* drastically increased in numbers post ~1950, replacing *Aulacoisera* as the most abundant group. Traditionally, an increase in small, benthic *Fragilaria* populations is considered a sign of colder water and increasing ice cover (Lotter & Bigler, 2000; Rühland et al., 2008); however, this contrasts with a warming climate scenario. The ecology of small, benthic *Fragilaria* is not well understood (Bennion et al., 2010), but in general, *Fragilaria* diatoms are likely to be fast-growing, opportunistic, r-selected species, allowing them to adapt to and colonize quickly in changing environmental conditions (Bennion et al., 2010; Lotter & Bigler, 2000). They have been found in a wide range of environments, from eutrophic to oligotrophic lakes (e.g. Bennion et al., 2001; Michelutti et al., 2002; Reavie et al., 1995).

Small, benthic *Fragilaria* are alkaliphilous, and it is possible that a warming climate has likely been enhancing the weathering of carbonate-rich sedimentary bedrock, increasing the alkalinity of the water, thus favouring the taxa (Karst-Riddoch et al., 2005). Alternatively, the increase in small, benthic *Fragilaria* could be a response to changing winter conditions and not changes during the open-water season. For example, enhanced diatom productivity might be occurring during the winter because of thinner ice conditions, enhanced under-ice light penetration, and/or periodic loss of ice cover over the winter instead of changes occurring during

the open-water season. Small, benthic *Fragilaria* are adapted to low-light conditions and are common pioneer species in ice-dominated Arctic lakes (Laing et al. 1999). I would expect small, benthic *Fragilaria* to dominate the winter algal community, and an increase in algal productivity over the winter could theoretically manifest as an increase in small, benthic *Fragilaria* relative abundance in sediment cores. This hypothesis should be investigated in future studies, as climate warming is projected to continue in the region (Ontario Climate Consortium, 2020).

6.2 Holocene Diatom Assemblages in the West Basin Corresponds to Previously Suggested Holocene Climate Conditions

Mastogloia smithii was the dominant species in early Holocene history (~7600 BP to ~6000 BP) of the west basin of Lake Scugog. *M. smithii* is an epiphytic diatom species that is characterized by its preference for cold, calcareous, oligotrophic waters (Gaiser et al., 2010; Sivaci et al., 2008). *Navicula diluviana* – a post-glacial pioneer species (Krause et al., 2014) – is also another epiphytic species found in this zone that thrives in cold, alkaline, oligotrophic waters (Campbell et al., 1997; Karst & Smol, 2000; Robertsson, 1995). The dominance of oligotrophic species, especially *M. smithii* which have commonly been used as an indicator species of oligotrophy (McCormick et al., 1996), suggests that the early post-glacial wetland was low in nutrients.

The opposite trends in abundance between *M. smithii* and *Neidium* spp. recorded from ~6000 BP to ~3500 BP might signal fluctuations in water levels. *N. ampliatum* and *N. iridis* both occupy epilithic and epipelic habitats (Cetin, 2008; Mann & Chepurnov, 2005; Štefková, 2006), therefore they can tolerate low water levels better than the epiphytic *M. smithii* which need higher water depths to support the macrophytes they grow on. Moreover, *Neidium* spp. can thrive in both oligotrophic and mesotrophic conditions (Lemly & Dimmick, 1982; Van Dam et al.,

1994), suggesting that there might have been more nutrients in the water during periods when *Neidium* spp. were dominant over *M. smithii*. Therefore, periods in which *Neidium* spp. were more abundant might be signals of warmer and drier conditions. Increased trophic status and primary production were also recorded for warmer temperatures and lower water periods during the Holocene in Ontario lakes (e.g. Karmakar et al., 2015; Moos et al., 2009). This could be attributed to a decrease in phosphorus flush out and subsequent increase in its detainment into the lake water and sediment (Bertahas et al., 2006), or internal phosphorus recycling due to wind-generated sediment resuspension (Søndergaard et al., 1992).

In contrast, periods in which *M. smithii* was more dominant than *Neidium* spp. might be signals of cooler and wetter climate conditions that would result in lake oligotrophication and increased water levels (Gushulak et al., 2021). Increases in water levels likely resulted in lower water retention times, thus reducing the amount of nutrients available for primary production (Bertahas et al., 2006). Oligotrophication could also help to increase water clarity (Gushulak & Cumming, 2020; Kingsbury et al., 2012), creating a more favoured condition for photosynthesis for macrophytes that *M. smithii* attached to (Middelboe & Markager, 1997). Increased water levels and clarity could potentially help macrophytes grow bigger and deeper – expanding the habitats for *M. smithii* and increasing its abundance. Furthermore, more established macrophytes could reduce wind-reduced wave activity and sediment resuspension, subsequently lower light attenuation (James et al., 2004), thus creating favourable conditions for even more macrophytes to grow.

M. smithii also showed a general trend of declining in abundance from ~6000 BP to ~3500 BP, going from maximum relative abundance of over 80% to only about 35%. This period also corresponded to the 6-3 ka BP dry period in southern Ontario and Kawartha Lakes region

suggested by Yu and McAndrews (1994), Sonnenburg et al. (2012) and Liefert and Shuman (2020). Based on the diatom trends, Lake Scugog indeed went through the same drought period as the rest of southern Ontario and the Kawartha Lakes region, with minimum lake level at ~3000 BP (Liefert & Shuman, 2020) – marked by the absence of *M. smithii* and highest abundances of *Neidium* spp. However, there were still fluctuations in precipitation during this period, as evidenced by the alternations in abundances between *M. smithii* and *Neidium* spp.

These precipitation fluctuations during the drought were not prominent in most other Holocene records in the region. However, most of these studies used pollen – which is more suitable to detect changes in terrestrial ecosystems (Bennett & Willis, 2001) or had low resolution, therefore they were not able to detect small changes. In contrast, the ancient Lake Scugog was a shallow marsh (Kawartha Conservation, 2010), and therefore was very sensitive to climatic changes. Diatoms are also a sensitive indicator of limnological changes, thus the diatom assemblages in Lake Scugog being able to track these fluctuations. Yu et al. (1997) also recorded stable isotope $\delta^{13}C$ fluctuations in Crawford Lake during the drought between 4.8 ka BP and 2 ka BP. The study suggested that an increase in $\delta^{13}C$ might be a signal of evaporative enrichment and/or lake productivity. It is possible that both the diatom records in Lake Scugog and the $\delta^{13}C$ values in Crawford Lake have recorded notable fluctuations in precipitation during the 6-3 ka BP drought in southern Ontario that other studies with less sensitive indicators could not detect.

The drought is suggested to have ended by ~3000 BP and by ~2000 BP, the precipitation rates were similar to modern day (Conolly, 2020). As lake levels gradually recovered, *Neidium* spp. slowly decreased. However, *M. smithii* did not make a recovery in abundance. Instead, other epiphytic taxa started to increase in relative abundances during this period. *Cymbella ehrenbergii* is an epiphytic/epilithic species (Bose & Pal, 2017; Hafner et al., 2013) that like oligo-

mesotrophic calcareous waters (Campbell at el., 1997; Van Dam et al., 1994). *Stauroneis phoenicenteron* is an epiphytic meso-eutrophic species (Hafner et al, 2013; Van Dam et al., 1994). *Amphora* spp. is also an epiphytic group, with *A. lybica* prefers mesotrophic and *A. ovalis* prefers eutrophic conditions (Campbell et al., 1997; Hafner & Jasprica, 2013; Van Dam et al., 1994). The ecology of these taxa seems to indicate that they would thrive in higher trophic conditions that are unfavourable to the oligotrophic *M. smithii*. This suggests that nutrients were the controlling factor instead of or in addition to water levels in Lake Scugog post ~3000 BP and to the top of the core (~2000 BP). It is possible that the ancient Lake Scugog was transitioning from oligotrophic to mesotrophic conditions through lake ontogeny – the natural progression of lake trophic states due to maturation of the landscape (Engstrom & Fritz, 1988).

6.3 Diatom Assemblages in the West Basin Show Evidence of Ecological Changes Caused by the Formation of the Lindsay Dam

The Holocene piston core and the gravity core of the west basin of Lake Scugog were collected from the same location, therefore they could be considered parts of a continuous paleolimnological record. However, the piston core started at ~2000 years BP, and the gravity core likely only goes back as far as ~1300 based on extrapolated ^{210}Pb dates (Wiklund & Hall, 2017), therefore there is a ~1000+ years gap between the two sediment cores.

Prior to the formation of the Lindsay Dam, the diatom assemblages in the bottom of gravity core seemed to continue the trends observed in the Holocene, being dominated by *Neidium* spp. and notably *Mastogloia smithii*. The recovery of *M. smithii* at the bottom of the gravity core despite its absence at the top of the piston core indicates that pre-modern Lake Scugog was still in relatively oligotrophic conditions, suggesting minimal impacts from early human settlements.

Following complete impoundment, reservoirs often go through a period of increasing primary production due a large influx of nutrients into the lake from biomass of flooded terrestrial material, increasing water levels and other factors (Hall et al., 1998; Kimmel et al., 1990). Despite water level increases likely associated with increases in *M. smithii* abundances in the Holocene, post-dam eutrophic conditions would not be favourable for the oligotrophic *M. smithii*, and instead the post-dam increase in water levels and the formation of Lake Scugog corresponded to an increase in small, benthic *Fragilaria* taxa. The period of trophic upsurge after inundation may last from 5 to 20 years (Kimmel et al., 1990). Interestingly, while the diatom assemblages did not show indications of trophic changes past this period, algal pigment analysis of the top 40 cm of the same core (Korosi et al., 2021) showed a clear transition from trophic upsurge to a period of reduced productivity. From 40 cm to 31 cm, pigment composition contained okenone, a pigment produced by purple sulfur phototrophic bacteria (Family Chromatiaceae). Okenone is considered an indicator of sedimentary anoxia, as purple sulfur bacteria are anaerobes that live in anoxic habitats such as stagnant waterbodies (Hunter et al., 2009). The presence of okenone likely indicated a period of trophic upsurge, as oxygen consumption during decomposition of a large amount of submerged material would cause anoxic conditions in Lake Scugog. Based on ^{210}Pb date, 31 cm depth (~1900) marked the end of the trophic upsurge, which would put the duration of this period at ~50 years.

In contrast to the east basin, planktonic diatoms only made up a small portion of the post-1844 diatom assemblages in the west basin, reflecting the differences in water depths between the two arms of the lake (7.5 m versus 2.5 m). Overall, the diatom composition did not exhibit any significant change since the formation of the lake – consistently being dominated by small, benthic *Fragilaria*. A similar response was observed in Lake Opinicon (southeastern Ontario,

Greater Kingston Area), which is also a shallow, macrophyte-dominated lake. Lake Opinicon experienced flooding after the construction of the Rideau Canal between 1828 and 1832. For ~45 years after inundation, small, benthic Fragilaria increased by 15% to represent approximately 95% of the assemblages and maintained dominance throughout history of the lake (Karst & Smol, 2000).

As mentioned above, small, benthic *Fragilaria* are highly adaptable, colonizing a wide range of environmental conditions. The diatom assemblages in the west basin have showed resilience to various changing conditions throughout recent history, especially eutrophication and watershed development. This lack of response in a diatom community dominated by small, benthic *Fragilaria* to eutrophication was expected as these taxa has been known to be poor indicators of lake trophic status (Bennion et al., 2010). However, it seems that these taxa are also very resilient to other changes in surface water temperatures, salinity, and invasive species as well.

CHAPTER SEVEN: CONCLUSIONS AND FUTURE WORK

7.1 General Conclusions

The Holocene diatom assemblages of the west basin of Lake Scugog covered the period of ~7600 to ~2000 BP. The dominance of the oligotrophic epiphytic *Mastogloia smithii* prior to ~3500 BP indicated low nutrient conditions in ancient Lake Scugog. From ~6000 BP to ~3500 BP, *M. smithii* declined in abundance, while the epilithic/epipelic oligo-mesotrophic *Neidium* spp. (consist of *Neidium ampliatum* and *Neidium iridis*) that can thrive in lower water levels increased in abundance. This indicated that Lake Scugog region went through a mid-Holocene drought that was previously suggested for southern Ontario and Kawartha Lakes region. Fluctuations in abundances of *M. smithii* and *Neidium* spp. during this period indicated variations in precipitation during the drought that were not documented in other Holocene records of the region. The diatom assemblages continued to be dominated by *M. smithii* and *Neidium* spp. prior the complete impoundment in 1844, before changing to a community dominated by small, benthic *Fragilaria* post-dam. The small, benthic *Fragilaria* are highly adaptable, therefore the diatom community did not show any significant response to the various recent changes affecting Lake Scugog such as eutrophication, increasing salinity, invasive species and climate change.

In contrast to a lack of response to watershed development and climate change in the west basin, the modern-day diatom assemblages in the east basin of Lake Scugog showed a transition corresponding to increased thermal stratification ca. 1950, consistent with a classic response to climate warming that has been recorded in many other lakes across the Northern Hemisphere. The planktonic diatom community went from being dominated by heavy, tychoplanktonic *Aulacoisera* to small, buoyant, cyclotelloid *Cyclotella*, most notably *Cyclotella ocellata*. Interestingly, small, benthic *Fragilaria* also became the most dominant taxa in the west

basin post ~1950, which might be a response to thinner ice conditions and increasing ice-free periods during wintertime.

7.2 Future Directions

Due to COVID-19 pandemic restricting lab access, the analysis of the sediment cores was limited to diatoms. However, the initial plan of this research was to reconstruct paleoenvironmental change in Lake Scugog using diatoms and pollen as biological indicators. Pollen and diatoms are indictive of different environmental variables and often used together as complementary proxy indicators in paleolimnological research. A multiproxy pollen and diatoms dataset can present robust arguments about the impacts of past climate changes and human impacts on both terrestrial and aquatic ecosystems. Studying the connections between terrestrial and aquatic responses to climatic changes will provide significant insight into how the biosphere responds to climatic changes, as well as the relationship between different ecosystems (Finkelstein et al., 2005). Additional sediment physical and geochemical proxies can also further refine paleoenvironmental reconstructions.

During the process of diatom identification in each slide, while most diatom fossils in the bottom intervals of the Holocene piston core were broken up, numerous very well-preserved pollen fossil were detected, suggesting the potential for successful pollen analysis. As past studies had successfully used integrated diatom and pollen dataset to reconstruct past climate of Ontario, this is a proven suitable approach for studying paleoclimatic conditions of Lake Scugog and the responses of the local aquatic and terrestrial ecosystems to climate change and human impacts after the European settlement.

As the west basin gravity core relied on loss-on-ignition to place the date of lake formation, and pigment data to identify the period of trophic upsurge, it is evident that integrating sediment geochemistry data would be beneficial. Loss-on-ignition and pigment analysis should also be carried out in the piston core to give complimentary data on changes in water level and trophic status, especially during the mid-Holocene drought.

The dominance of small, benthic Fragilaria in recent sediments of both west basin and east basin raises the need for other more sensitive indicators, especially for real-time winter monitoring. Cladocerans might be an excellent choice of complementary paleoecological proxy as they can track changes in lake trophic status (Korhola & Rautio, 2001). Furthermore, as Lake Scugog continues to transform from a macrophyte-dominated to an algal-dominated lake, cladocerans can help track significant changes in the food web (Korhola & Rautio, 2001).

As anthropogenic climate warming continues, the east basin of Lake Scugog might experience extended periods of thermal stratification, which could subsequently lead to deep-water hypoxia. Chironomids has been used as a sensitive indicator of hypolimnetic oxygen conditions, lake productivity and temperature (Walker, 2001). Whether Lake Scugog has undergone stratified periods prior to the Ontario Tech University monitoring program is unknown, therefore paleolimnological data on chironomids might give clue on the past mixing regimes. Real-time monitoring of chironomids assemblages might also give valuable information on how Lake Scugog is responding to current increasing surface water temperatures and thermal stratification driven by climate warming.

The ~1000+ years gap between piston core and gravity core in the west basin should also be addressed in a future study to complete the Holocene history record of Lake Scugog. Some important changes potentially had happened during that period, bringing back *M. smithii* and

oligotrophic conditions as seen prior to the construction of the Lindsay Dam. Alternatively, future research can also reconstruct the Holocene paleoenvironmental record for the east basin. That will provide insights on how two different basins responded to various climatic changes in the past – especially to the mid-Holocene drought, and give clues to how they might transform in the future.

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